JURNAL iafmi
edisi 18 • Desember 2025
Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia



Sustainable Energy Resilience:

Indonesia's Path to Self Sufficiency

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VISI MISI
JURNAL IAFMI

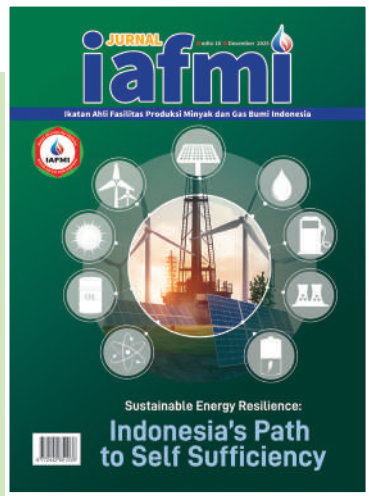
1. Membangun knowledge database yang kedepannya diharapkan dapat menjadi referensi utama ilmu dan teknologi dibidang fasilitas produksi migas di Indonesia, serta referensi kondisi lokal untuk International Codes.

2. Mendorong para professional dan akademisi dibidang fasilitas produksi migas untuk menerbitkan karya dan pemikirannya sehingga kompetensi dan keahliannya terangkat ke permukaan dunia industri migas.

3. Menjalin jaringan keilmuan dan teknologi untuk mengembangkan industri nasional dibidang fasilitas produksi migas.

4. Mengangkat aktifitas sumberdaya pendukung industri infrastruktur migas ke permukaan.

Dari Redaksi



Alhamdulillah, Jurnal IAFMI edisi ke-18 dapat terbit sesuai rencana di akhir tahun 2025 dengan tema *Sustainable Energy Resilience: Indonesia's Path To Self Sufficiency.* Pemilihan tema tersebut sejalan dengan Joint Convention (JC) yang telah sukses dilaksanakan Juli 2025 di Semarang, dimana tema terebut merupakan agenda besar pemerintah untuk mewujudkan ketahanan energi di Indonesia.

Melalui jurnal edisi ini, profesional fasilitas produksi migas di tanah air telah memberikan sumbang saran dan ide terkait pengetahuan, pendekatan (*methods*), atau pelajaran (*lessons learned*) sesuai dengan bidang keahliannya. Beberapa kata kunci yang ada di Jurnal edisi ke-18 ini diantaranya adalah *flare reduction, gas recovery, emission reduction, net zero-emission, sustainability,* kecerdasan buatan dan dekarbonisasi.

Bahasan Jurnal dimulai dengan paper pertama perihal strategi dan contoh program dekarbonasi yang dijalankan perusahaan nasional. Berikutnya mengenai bagaimana revitalisasi sumur marjinal di *offshore* melalui strategi optimisasi tekanan keluaran sumur. Terdapat juga paper tentang teknis mitigasi kondisi *electrical and mechanical strees* pada motor untuk aplikasi industri.

Jurnal ini juga memuat bahasan lain yaitu peningkatan keandalan produksi melalui strategi optimisasi lapangan migas dengan pendekatan *risk-based*, dan peningkatan integritas tanki timbun kondensat. Terkait AI (*Artificial Intelligence*), terdapat paper tentang *machine learning* untuk *data acquisition* dan optimasi produksi. Terdapat juga kajian sistem energi hibrida surya–diesel sebagai solusi energi berkelanjutan pada sebuah proyek konstruksi.

Sebagai bagian untuk mendukung inovasi dan transisi energi di industri migas, terdapat paparan komprehensif mengenai potensi produksi hidrogen rendah karbon berbasis biomassa di Indonesia. Secara umum, beberapa paper berisi *sharing* upaya-upaya pengurangan emisi di beberapa lapangan migas Indonesia sehingga dapat menjadi lessons learned untuk kemungkinan implementasi di lapangan migas lainnya.

Edisi kali ini juga merupakan edisi terakhir bagi kepengurusan IAFMI periode tahun 2022 – 2025. Dengan ini kami juga ingin menyampaikan terima kasih yang tulus kepada para pembangku kepentingan Jurnal IAFMI, baik pengurus dan sesama team redaksi Jurnal IAFMI maupun pemakalah dan penulis yang telah ikut mengirimkan naskah untuk penerbitan Jurnal dari edisi 13 hingga 18 ini.

Semoga tulisan yang disajikan dalam Jurnal ini dapat menambah dan memperkaya pengetahuan, jaringan dan pengalaman bagi para pembaca. Kami akan selalu menunggu masukan dan tulisan Profesional IAFMI semuanya untuk Jurnal IAFMI edisi 19 dan berikutnya. Sampai jumpa di kepengurusan IAFMI periode 2025 – 2028 yang lebih baik. Karena menulis adalah pekerjaan untuk berkontribusi dan mengabadikan nama dalam sejarah.

Salam,

Redaksi

Kata Pengantar

Ketua Umum IAFMI



Keamanan dan ketahanan energi merupakan hal yang fundamental bagi stabilitas ekonomi dan pembangunan berkelanjutan Indonesia. Lanskap energi Indonesia berakar kuat pada bahan bakar fosil konvensional, dan dengan fokus yang semakin besar pada sumber energi terbarukan. Meskipun energi terbarukan memainkan peran krusial dalam keberlanjutan, bahan bakar fosil tetap esensial dalam memastikan ketahanan energi. Pemerintah telah menetapkan target ambisius untuk meningkatkan keberlanjutan, sejalan dengan komitmen global untuk mengurangi emisi karbon. Namun, mencapai keamanan energi memerlukan penanganan kesenjangan infrastruktur, hambatan regulasi, dan batasan teknologi.

Jurnal IAFMI Edisi 18 ini dengan mengusung tema "Sustainable Energy Resilience: Indonesia's Path to Self Sufficiency". Dalam jurnal edisi ini akan memberikan beragam variasi pengetahuan terkait implementasi solusi dekarbonisasi dan teknologi low-carbon demi kemandirian energi. Paper yang masuk di dalam Jurnal edisi ini merupakan bukti jawaban atas tantangan di sektor energi nasional. Saya menyampaikan apresiasi yang setinggi-tingginya pada Dewan Redaksi Jurnal IAFMI dan anggota IAFMI yang telah bersedia dan berkontribusi baik secara langsung ataupun tidak langsung pada penulisan makalah untuk penerbitan Jurnal IAFMI Edisi 18.

Saya juga menyampaikan rasa apresiasi saya kepada para profesional fasilitas produksi migas atas dukungannya untuk Kongres IAFMI V 2025 yang telah diselenggarakan di di Hotel Sultan, DKI Jakarta, tanggal 6 Desember 2025. Kongres tersebut telah menentukan Ketua Umum IAFMI terpilih periode 2025-2028, serta arah masa depan IAFMI yang lebih tangguh dalam menghadapi tantangan di masa yang akan datang.

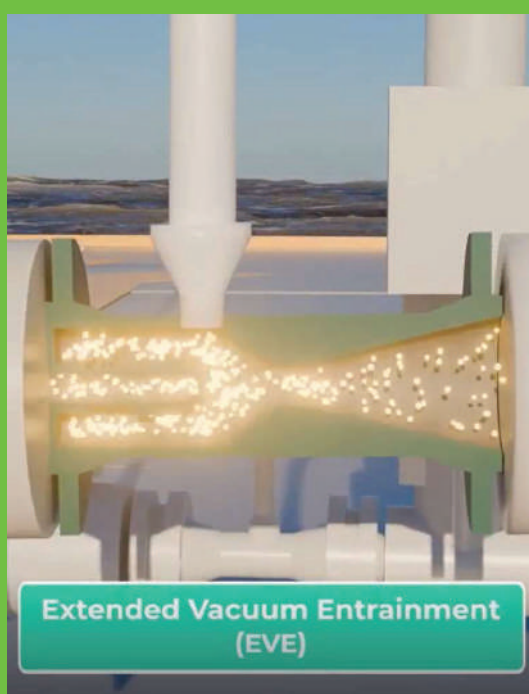
Akhir kata dengan kerendahan hati, saya selaku Ketua Umum IAFMI periode 2022-2025, mengucapkan terima kasih yang sebesar-besarnya kepada seluruh pihak yang telah memberikan dedikasi, waktu, tenaga, dan pikiran demi kemajuan organisasi kita tercinta selama periode kepengurusan saya. Ada banyak tantangan, dinamika, dan perubahan industri yang harus kita hadapi bersama. Namun berkat kolaborasi yang kuat, komitmen tanpa henti, dan semangat kebersamaan, kita mampu terus berkontribusi bagi kemajuan profesi fasilitas produksi migas di Indonesia.

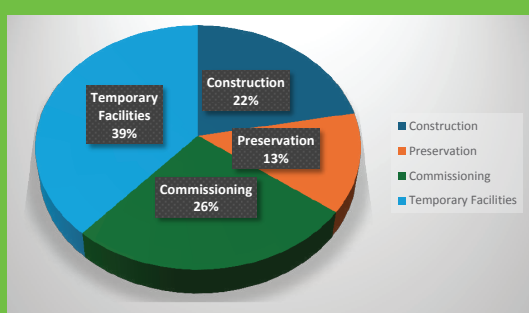
Dr. Ir Taufik Aditiyawarman, MM, PMP, IPU

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NUSANTARA ENERGY FORUM "ENERGIZING INDONESIA FOR A SUSTAINABLE FUTURE"

(20 AGUSTUS 2025)

IAFMI menerima undangan untuk berpartisipasi dalam Nusantara Energy Forum tanggal 20 Agustus 2025, yang kemudian diwakili oleh Bapak Ir. Andi M Palkar, ST, MSc , IPU, CEng MIMarEST, IEng MIMechE, sebagai Ketua Bidang Keahlian Mechanical Static dan Pipeline dan Bapak Juanto Sitorus, SSi, MT, CPM, CSEP, ERMCP, PMP, sebagai Ketua Bidang Keahlian Transformasi Digital dari IAFMI. Insight yang didapatkan dari pertemuan tersebut yaitu Pemerintah mendorong pemanfaatan Energi Baru Terbarukan (EBT) untuk elektrifikasi pedesaan melalui program Kementerian Desa dan Kementerian Dalam Negeri. Pemetaan potensi EBT solar, wind, hydropower, biomass, dan geothermal telah dilakukan di seluruh pulau untuk memastikan implementasi sesuai potensi daerah dan kebutuhan industri lokal. Kapasitas terpasang EBT meningkat dari 15 GW pada 2024 menjadi 46 GW pada 2025, dengan potensi nasional yang dapat melampaui 1.300 GW jika dimanfaatkan optimal. Selain EBT, pemerintah juga mengembangkan teknologi reaktor nuklir modern untuk kebutuhan listrik, kesehatan, hingga *food preservation*. Program ini menjadi bagian dari strategi bauran energi jangka panjang Indonesia. **[SHIFA]**

PENANDATANGAN MOU KERJA SAMA ANTARA IAFMI DAN ITB

(22 AGUSTUS 2025)

MoU (*Memorandum of Understanding*) kerja sama antara Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia (IAFMI) dan Institut Teknologi Bandung (ITB) resmi diperbarui melalui penandatanganan dokumen kesepakatan baru pada tanggal 22 Agustus 2025 di Kampus ITB. Pembaruan MoU ini ditandatangani oleh Ketua Umum IAFMI, Dr. Ir. Taufik Aditiyawarman, MM, PMP, IPU, dan Rektor ITB, Prof. Dr. Ir. Tatacipta Dirgantara, MT, sebagai bentuk komitmen



kedua belah pihak untuk melanjutkan serta memperkuat kolaborasi strategis yang telah terjalin sebelumnya.

Melalui pembaruan MoU ini, IAFMI dan ITB menegaskan kembali tujuan bersama dalam meningkatkan kualitas pendidikan, penelitian, dan pengembangan profesional di bidang fasilitas produksi minyak dan gas bumi. Kolaborasi ini diharapkan dapat memberikan kontribusi nyata bagi penguatan kompetensi sumber daya manusia, pengembangan inovasi teknologi, serta peningkatan kualitas kegiatan akademik dan keprofesian yang dijalankan oleh kedua institusi.

Selain itu, kesepakatan ini juga membuka peluang lebih luas untuk penyelenggaraan berbagai program bersama, seperti pelatihan, seminar, workshop, hingga kegiatan ilmiah lainnya yang dapat mendukung kebutuhan industri migas nasional. Dengan diperbaruinya MoU ini, IAFMI dan ITB berharap dapat terus berperan aktif dalam mendorong kemajuan sektor energi di Indonesia melalui sinergi yang berkelanjutan dan produktif. **[SHIFA]**

FOCUS GROUP DISCUSSION (FGD) PERSATUAN INSINYUR INDONESIA "INDONESIA ENERGY SUMMIT : PENINGKATAN LIFTING MIGAS UNTUK KETAHANAN NASIONAL"

(29 AGUSTUS 2025)

Indonesia Energy Summit dilaksanakan pada tanggal 29 Agustus 2025 dimana IAFMI diwakili oleh Bapak Ir. Andi M Palkar, ST, MSc , IPU, CEng MIMarEST, IEng MIMechE, sebagai Ketua Bidang Keahlian Mechanical Static dan Pipeline dan Bapak Wayan Mega Budiartha, ST , MT sebagai



Ketua Bidang Keahlian Project Management IAFMI dengan insight yang didapatkan yaitu Acara Persatuan Indonesia Insinyur (PII) Indonesia Energy Summit berlangsung dengan beberapa catatan penting. Ketua Umum PII tidak hadir pada kegiatan tersebut. Selain itu, Kepala SKK Migas yang dijadwalkan memberikan sambutan turut berhalangan hadir dan digantikan oleh Deputi Eksplorasi, Pengembangan, dan Manajemen Wilayah Kerja. Akibatnya, sesi speech SKK Migas yang sebelumnya tercantum dalam agenda tidak dilaksanakan. Format acara tidak berjalan sebagai Focus Group Discussion (FGD) sebagaimana diharapkan, melainkan hanya berupa presentasi para panelis dengan sesi tanya jawab yang terbatas. Materi pemaparan juga kurang menyoroti isu utama terkait upaya peningkatan lifting migas, sementara pembahasan downstream hanya disinggung secara singkat. Panelis lebih banyak memaparkan capaian keberhasilan lifting tanpa membahas tantangan yang dihadapi serta solusi yang diperlukan. [**SHIFA**]







LADIES PROGRAMME: PENDAKIAN GUNUNG PRAU

(13 SEPTEMBER 2025)

Pendakian Gunung Prau sebagai bagian "Ladies Programme" dilaksanakan pada 13 September 2025 merupakan salah satu kegiatan yang diinisiasi oleh IAFMI Hikers, komunitas pecinta alam di lingkungan IAFMI. Kegiatan ini dirancang khusus untuk memberikan ruang bagi para anggota, khususnya peserta perempuan, untuk merasakan pengalaman pendakian yang aman, menyenangkan, dan penuh kebersamaan.

Melalui kegiatan ini, para peserta diajak untuk mengeksplorasi keindahan Gunung Prau sekaligus menikmati suasana alam yang menyegarkan. Pendakian tidak hanya menjadi sarana olahraga dan rekreasi, tetapi juga wadah untuk membangun semangat tim, melatih ketahanan diri, serta memperkuat rasa percaya diri dalam menghadapi tantangan di lapangan.

Selain itu, kegiatan ini turut menanamkan nilai kepedulian terhadap lingkungan melalui praktik pendakian yang bertanggung jawab, seperti menjaga kebersihan jalur, meminimalkan sampah, dan menghargai ekosistem setempat. Interaksi yang terjalin selama perjalanan, baik dalam obrolan ringan, saling membantu, maupun berbagi pengalaman, menjadi bagian penting dalam mempererat hubungan antaranggota. Secara keseluruhan, Pendakian Gunung Prau "Ladies Programme" tidak hanya menghadirkan pengalaman petualangan dan kebugaran fisik, tetapi juga memperkuat ikatan komunitas, membangun karakter, serta menciptakan kenangan berharga bagi seluruh peserta. [**SHIFA**]



EVALUASI JOINT CONVENTION SEMARANG (JCS) 2025

(14 SEPTEMBER 2025)

Sebuah acara yang berlangsung meriah dan penuh suasana keakraban. Kegiatan ini menjadi penanda resmi berakhirnya seluruh rangkaian pelaksanaan JCS 2025, sekaligus sebagai bentuk apresiasi atas dedikasi dan kerja keras yang telah diberikan oleh seluruh panitia sejak tahap perencanaan hingga pelaporan akhir.

Dalam acara tersebut, panitia menyampaikan laporan pertanggungjawaban secara lengkap sebagai penutup masa tugas mereka. Penyampaian laporan ini menjadi simbol bahwa seluruh amanah, tanggung jawab, serta kewajiban penyelenggaraan kegiatan telah dijalankan dengan baik dan transparan. Setelah seluruh rangkaian agenda selesai, struktur kepanitiaan secara resmi dinyatakan dibubarkan.

Momentum pembubaran ini tidak hanya menjadi akhir dari masa kerja panitia, tetapi juga menjadi kesempatan untuk mempererat hubungan antar anggota, mengenang proses yang telah dilalui bersama, serta mengapresiasi kontribusi setiap individu yang telah memberikan waktu, tenaga, dan komitmen demi terselenggaranya JCS 2025 dengan sukses. [**SHIFA**]

PENANDATANGANAN MOU ANTARA IKATAN IAFMI DAN SKK MIGAS

(8 OKTOBER 2025)

Penandatanganan MoU (*Memorandum of Understanding*) ini sebagai tindak lanjut dari kerja sama yang telah terjalin sebelumnya antara Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia (IAFMI) dan Satuan Kerja Khusus Pelaksana Kegiatan Usaha Hulu Minyak dan Gas Bumi (SKK Migas), sehingga menjadi langkah







strategis yang menegaskan kembali komitmen kedua pihak dalam memperkuat sinergi, khususnya dalam pengembangan kompetensi dan peningkatan kapasitas profesional di sektor hulu migas.

Melalui pembaruan MoU ini, kedua belah pihak menekankan pentingnya kolaborasi berkelanjutan untuk mendukung berbagai program strategis industri hulu migas nasional. Kesepakatan ini mencakup peluang kerja sama yang lebih luas, mulai dari penyelenggaraan pelatihan, sertifikasi keahlian, seminar, hingga kegiatan yang berfokus pada peningkatan kualitas tenaga ahli di bidang fasilitas produksi minyak dan gas.

IAFMI dan SKK Migas berharap bahwa kerja sama yang diperbarui ini dapat menghadirkan program-program yang lebih relevan, adaptif, dan sesuai dengan perkembangan teknologi serta kebutuhan industri. Dengan demikian, sinergi yang dibangun tidak hanya memperkuat kualitas sumber daya manusia, tetapi juga memberikan kontribusi nyata terhadap kemajuan industri migas Indonesia secara berkelanjutan. **[SHIFA]**

PRESENTATION & DISCUSSION BP ENERGY OUTLOOK

(10 OKTOBER 2025)

Sebagai partisipan pada acara tersebut IAFMI diwakili oleh Ibu Desi Aresa Mahdi, ST, MBA, PMP, PMI-ACP, selaku Direktur Eksekutif dan Bapak Ir. G. Daru P. Dewanto, S.T., M.M., M.B.A., IPM. selaku Sekretaris Jenderal IAFMI. Partisipasi ini bertujuan untuk memperoleh pemahaman terbaru mengenai proyeksi energi global, dinamika pasar migas, serta tren transisi energi yang disampaikan oleh bp. Kehadiran perwakilan IAFMI di forum tersebut diharapkan dapat memperkaya wawasan organisasi dalam menyusun rekomendasi strategis serta mendukung kolaborasi dengan pemangku kepentingan di sektor energi.

FOCUS GROUP DISCUSSION (FGD) "SUSTAINABILITY IN PROJECT MANAGEMENT"

(11 OKTOBER 2025)

Sebagai narasumber pada acara Focus Group Discussion (FGD) "Sustainability in Project Management" yang diselenggarakan oleh Program Magister Manajemen UGM Jakarta pada tanggal 11 Oktober 2025, IAFMI memberikan pemaparan terkait integrasi prinsip keberlanjutan dalam perencanaan, eksekusi, dan pengendalian proyek. Partisipasi ini bertujuan untuk berbagi pengalaman praktis, memperkuat pemahaman peserta mengenai tantangan dan peluang penerapan sustainability di berbagai sektor industri, serta mendorong kolaborasi akademisi–praktisi dalam pengembangan praktik manajemen proyek yang lebih berkelanjutan. **[SHIFA]**

FOCUS GROUP DISCUSSION (FGD) "PENGEMBANGAN SISTEM SINKRONISASI DATA BAWAH PERMUKAAN HULU MIGAS BERBASIS INTERKONEKSI GIS"

(22-24 OKTOBER 2025)

Sebagai partisipan pada acara Focus Group Discussion (FGD) "Pengembangan Sistem Sinkronisasi Data Bawah Permukaan Hulu Migas Berbasis Interkoneksi GIS" yang dilaksanakan pada tanggal 22–24 Oktober 2025, IAFMI berperan dalam memberikan masukan teknis serta pandangan strategis terkait kebutuhan standardisasi, integrasi, dan pemanfaatan data bawah permukaan. Melalui forum ini, peserta berdiskusi mengenai pengembangan sistem interkoneksi GIS yang mampu meningkatkan akurasi, efisiensi, serta kolaborasi antar pemangku kepentingan di industri hulu migas. Partisipasi IAFMI diharapkan dapat mendukung upaya penguatan tata kelola data dan percepatan transformasi digital di sektor migas nasional. **[SHIFA]**

UPACARA PERINGATAN HARI JADI PERTAMBANGAN DAN ENERGI KE-80 TAHUN 2025 | (24 OKTOBER 2025)

Sebagai partisipan pada acara Upacara Peringatan Hari Jadi Pertambangan dan Energi ke-80 Tahun 2025 yang diselenggarakan oleh Kementerian Energi dan Sumber Daya Mineral Republik Indonesia pada tanggal 24 Oktober 2025, IAFMI turut hadir sebagai bentuk dukungan terhadap perjalanan dan kontribusi sektor pertambangan serta energi nasional. Kehadiran IAFMI dalam upacara ini mencerminkan komitmen organisasi untuk terus memperkuat kolaborasi dengan pemerintah dan pemangku kepentingan terkait, serta berkontribusi dalam pengembangan kebijakan dan inovasi yang mendorong keberlanjutan sektor energi di Indonesia. **[SHIFA]**

INSTITUT TEKNOLOGI BANDUNG ENERGY TRANSITION SUMMIT 2025, TANGGAL 13 NOVEMBER 2025 | (13 NOVEMBER 2025)

Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia (IAFMI) turut berpartisipasi dalam kegiatan Institut Teknologi Bandung Energy Transition Summit 2025 yang diselenggarakan pada tanggal 13 November 2025. Dalam acara tersebut, IAFMI diwakili oleh dua perwakilan utama, yaitu Bapak Ir. Rifkiandi Darajatun, ST., MBA, IPM, CSRS., selaku Ketua Bidang Sustainability Industri Migas, dan Bapak Ir. Batara Purba, MM, PMP, selaku Ketua Bidang Pemberdayaan Industri







Dalam Negeri dan Sumber Daya Pendukung.

Summit ini diselenggarakan sebagai fo-rum strategis untuk membahas arah dan tantangan transisi energi di Indonesia melalui pendekatan kebijakan, analisis tekno-ekonomi, pengembang-an teknologi, serta pembangunan kapasitas manusia. Kehadiran IAFMI dalam forum penting ini menegaskan komitmen organisasi untuk berkontribusi dalam dialog nasional mengenai transformasi energi dan kesiapan sektor migas menghadapi perubahan dinamika global.

Dalam kegiatan tersebut, para perwakilan IAFMI memberikan pandangan mengenai peluang dan strategi pengembangan energi yang lebih berkelanjutan, pentingnya inovasi teknologi, serta penguatan kompetensi sumber daya manusia sebagai kunci keberhasilan transisi energi. Diskusi yang berlangsung diharapkan dapat memberikan masukan konstruktif bagi ITB sebagai institusi akademik, bagi pemerintah sebagai pembuat kebijakan, serta bagi pelaku industri sebagai garda depan implementasi strategi transisi energi. Partisipasi IAFMI dalam summit ini tidak hanya memperkuat sinergi antara akademisi, industri, dan regulator, tetapi juga memperluas kontribusi organisasi dalam mendorong kebijakan energi yang lebih adaptif, inklusif, dan berkelanjutan bagi masa depan sektor energi Indonesia. [**SHIFA**]

CAMPING PENGURUS IAFMI "SATU JEJAK SATU CERITA"

(15-16 NOVEMBER 2025)

Camping Pengurus IAFMI dilaksanakan pada tanggal 15–16 November 2025 di Rumamera, berada di ketinggian 1.040 mdpl di sisi Barat Daya Gunung Pangrango yang memiliki puncak tertinggi ±3.019 mdpl. Lokasinya tepat berada di luar perbatasan Taman Nasional Gunung Gede Pangrango (TNGGP).





Acara berlangsung dengan sukses dan meninggalkan kesan mendalam bagi seluruh peserta. Mengusung tema "Satu Jejak Satu Cerita", kegiatan ini dirancang sebagai momentum bagi para pengurus untuk beristirahat sejenak dari rutinitas organisasi, sekaligus memperkuat hubungan dan mempererat sinergi dalam suasana yang lebih santai dan natural.



Selain itu, suasana hangat di tengah alam terbuka menghadirkan ruang bagi para pengurus untuk saling mengenal lebih dekat di luar konteks formal organisasi. Kebersamaan yang terjalin selama camping menjadi sarana untuk memperkuat rasa kekeluargaan, meningkatkan kolaborasi, serta menciptakan cerita-cerita baru yang memperkaya perjalanan kolektif IAFMI.

Secara keseluruhan, kegiatan ini tidak hanya menjadi ajang penyegaran pribadi dan kebersamaan, tetapi juga memberikan energi baru bagi para pengurus untuk melangkah lebih kompak dan penuh semangat dalam menjalankan program serta tujuan organisasi ke depannya. [**SATIR**]

FOCUS GROUP DISCUSSION (FGD) TERKAIT PERSEPSI STAKEHOLDER PT KILANG PERTAMINA INTERNASIONAL (KPI)

(18 NOVEMBER 2025)

Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia (IAFMI) kembali mendapatkan





kepercayaan sebagai narasumber dalam kegiatan Focus Group Discussion (FGD) yang diselenggarakan oleh Lembaga Manajemen Fakultas Ekonomi dan Bisnis Universitas Indonesia (LM FEB UI) pada tanggal 18 November 2025. Dalam kesempatan ini, IAFMI diwakili oleh Ibu Ir. Corina Permatasari selaku Wakil Bidang Pemberdayaan Industri Dalam Negeri dan Sumber Daya Pendukung.

FGD tersebut menghadirkan berbagai



pemangku kepentingan dari sektor migas dan lembaga akademik untuk membahas topik strategis terkait Persepsi Stakeholder PT Kilang Pertamina Internasional (KPI). Melalui kehadirannya, IAFMI memberikan sudut pandang profesional mengenai dinamika operasional industri hilir migas, tantangan yang dihadapi KPI dalam meningkatkan kinerja dan layanan, serta peluang sinergi yang dapat dibangun melalui kolaborasi lintas sektor.

Ibu Corina menyampaikan pandangan mengenai pentingnya membangun hubungan yang kuat dan transparan antara perusahaan dan para pemangku kepentingannya. Beliau juga menyoroti peran inovasi, pemanfaatan sumber daya dalam negeri, serta penguatan kapabilitas SDM sebagai elemen kunci dalam meningkatkan kepercayaan stakeholder dan daya saing industri.

Kehadiran IAFMI dalam FGD ini tidak hanya mencerminkan kontribusi organisasi sebagai mitra ekspertis yang kredibel, tetapi juga memperluas ruang kolaborasi antara IAFMI, dunia akademik, dan industri. Melalui dialog konstruktif ini, diharapkan hasil diskusi dapat menjadi masukan strategis bagi PT KPI dalam merumuskan kebijakan, strategi komunikasi, dan langkah pengembangan ke depan. **[SHIFA]**



KONGRES V IAFMI

Pemilihan Ketua IAFMI 2025 - 2028

Ikatan Ahli Fasilitas Produksi Minyak dan Gas Bumi Indonesia (IAFMI) menyelenggarakan Kongres V di Jakarta pada Sabtu, 6 Desember 2025. Kegiatan ini menjadi forum strategis bagi organisasi dalam menetapkan arah pengembangan asosiasi serta memilih kepengurusan baru untuk periode 2025–2028. Sebagai organisasi profesi yang menaungi para ahli fasilitas produksi migas di Indonesia, IAFMI terus berkomitmen untuk menjadi wadah kolaborasi, penguatan kompetensi, serta pertukaran pengetahuan teknis bagi para profesional di sektor hulu migas.



Pada kesempatan tersebut, Ketua Umum IAFMI periode 2022–2025, Bapak Dr. Ir. Taufik Aditiyawarman, MM, PMP, IPU, memaparkan laporan pertanggungjawaban yang memuat capaian program, perkembangan kegiatan, serta pertumbuhan keanggotaan selama masa kepemimpinannya. Sebagai wujud transparansi organisasi, dokumen laporan lengkap akan tersedia di situs resmi IAFMI mulai Senin, 8 Desember 2025.



Sebagai bentuk apresiasi atas dedikasi dan kontribusi pengurus periode sebelumnya,





Kongres turut melakukan penyerahan plakat penghargaan IAFMI kepada Ketua Umum beserta jajaran pengurus 2022–2025. Momen ini menjadi simbol penghormatan sekaligus pengakuan atas fondasi organisasi yang telah diperkuat selama dua periode kepemimpinan.

Selain agenda laporan pertanggungjawaban, Kongres V juga mengesahkan sejumlah perubahan pada Anggaran Dasar dan Anggaran Rumah Tangga (AD/ART). Revisi tersebut dilakukan untuk memperkuat tata kelola asosiasi, meningkatkan efektivitas organisasi, dan menyesuaikan arah strategi kelembagaan dengan dinamika industri migas nasional yang terus berkembang. Proses pembahasan berlangsung secara konstruktif dan partisipatif, mencerminkan kedewasaan organisasi dalam menetapkan kebijakan internal.





Agenda utama kongres adalah pemilihan Ketua Umum IAFMI periode 2025–2028, dengan dua kandidat yaitu:

- **Bapak 3. Ir. Luky A. Yusgiantoro, BSc, MSc, MSpec (IFP), PhD, IPU, ASEAN Eng,** Sekretaris SKK Migas, dan
- **Ir. Gede Pramona, ST,** Direktur Pengembangan dan Operasional PT Titis Sampurna Inspection.

Proses pemilihan berlangsung secara kondusif dan menjunjung semangat kekeluargaan antar anggota. Dalam forum, Bapak Gede Pramona menyampaikan dukungan kepada Luky Yusgiantoro, sehingga melalui keputusan aklamasi, Bapak **Luky Yusgiantoro resmi ditetapkan sebagai Ketua Umum IAFMI periode 2025–2028**.

Dalam pidato perdananya, Bapak Luky menyampaikan visi memperluas jangkauan aktivitas IAFMI di tingkat nasional maupun internasional, serta memperkuat peran chapter sebagai pusat pengembangan kompetensi dan kolaborasi anggota. Ia juga menekankan pentingnya mempererat komunikasi internal, memperluas jejaring eksternal, dan menyesuaikan program organisasi dengan kebutuhan industri







migas yang terus berkembang.

Bapak Luky turut memberikan penghargaan kepada Bapak Taufik Aditiyawarman atas kontribusinya selama dua periode kepemimpinan. Beliau menyatakan bahwa fondasi yang telah dibangun menjadi modal penting bagi pengembangan program, inovasi, dan keberlanjutan organisasi di masa mendatang.

Kongres V IAFMI mencerminkan konsistensi asosiasi dalam memperkuat tata kelola, memperluas program yang berdampak, serta menjawab tantangan perkembangan teknologi dan kebutuhan industri nasional. Kehadiran para anggota dari berbagai wilayah dan latar belakang keahlian menunjukkan soliditas komunitas IAFMI sekaligus mempertegas peran asosiasi sebagai pusat keilmuan dan praktik terbaik (*best practices*) dalam manajemen dan operasi fasilitas produksi migas.

Sebagai momentum penting bagi regenerasi organisasi, Kongres V menjadi pijakan strategis untuk meningkatkan kontribusi IAFMI dalam pengembangan kompetensi profesional, keselamatan proses, efisiensi operasi, keberlanjutan fasilitas produksi, serta daya saing industri migas nasional di masa mendatang. **[SHIFA]**

DECARBONIZING INDONESIA'S UPSTREAM: ZERO ROUTINE FLARING INITIATIVE

Hanto Yananto and Awan Pinosofa
PT. Pertamina Hulu Energi, Jakarta, Indonesia

ABSTRACT

Indonesia is among the top contributors to global greenhouse gas emissions from routine flaring, a practice that wastes valuable energy resources and exacerbates climate change. To address this pressing issue, the Indonesian government has committed to achieving zero routine flaring in its upstream oil and gas sector by 2030. As the nation's state-owned oil and gas company, Pertamina plays a critical role in achieving this ambitious target. This paper examines the feasibility and potential impact of Indonesia's Zero Routine Flaring initiative, focusing on Pertamina's strategies, challenges, and opportunities in implementing this program within its upstream operations. The analysis examines gas utilization projects, technological advancements, and policy frameworks, offering insights into Pertamina's decarbonization journey and its role in shaping a sustainable energy future.

1. INTRODUCTION

Routine gas flaring is a persistent issue in the global oil and gas sector. According to the World Bank (2022), approximately 144 billion cubic meters of gas were flared globally in 2021, releasing over 400 million tons of CO_2 equivalent. Indonesia ranks among the top ten gas-flaring countries, with significant volumes emitted from upstream operations due to infrastructure constraints, economic disincentives, and outdated practices.

In response, the Indonesian government has pledged to achieve zero routine flaring (ZRF) by 2030, a commitment reinforced through participation in the World Bank's Zero Routine Flaring Initiative. This aligns with Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement and its Net Zero Emissions roadmap for 2060.

This paper aims to assess the effectiveness of Pertamina Hulu Energi's (PHE) ZRF strategies in addressing Indonesia's upstream flaring challenges. It also analyzes the regulatory and economic frameworks that shape flare gas management, seeking to identify technologies and practices that can be scaled across similar upstream contexts. By focusing on field-tested solutions, the study intends to contribute to a broader understanding of what makes flare reduction viable in terms of technical performance, economic returns, and regulatory alignment. The relevance of this study is grounded in the urgent need for actionable decarbonization pathways within the oil and gas industry, particularly in countries with high flaring volumes and infrastructure constraints. In doing so, the study offers a replicable model for operators facing

similar challenges in emerging economies.

The study is framed by the theoretical underpinnings of environmental economics and energy transition theory, particularly the Porter Hypothesis, which posits that strict environmental regulations can spur innovation and efficiency.

Routine flaring has historically been practiced in oil and gas operations to dispose of associated gas that could not be economically utilized. In Indonesia, flaring is driven by remote field locations, limited infrastructure, and economic disincentives for gas utilization. According to the World Bank's Global Gas Flaring Reduction Partnership (GGFR), Indonesia has consistently ranked among the top ten countries for flaring volumes (Figure 1).

using or conserving, associated gas, a by-product of oil production. The flaring of gas contributes to climate change and impacts the environment through the emission of CO2, black carbon, and other pollutants. It also wastes a valuable energy resource that could be used to advance the sustainable development of producing countries.

2. METHODOLOGY

This study adopts a qualitative case study approach, which is well-suited for exploring complex real-world phenomena within their contextual settings. The decision to use this methodology is based on the need to examine not just what technologies were implemented to reduce routine flaring, but also how and why



Figure 1. *Top Routine Flaring Countries (Source: World Bank GGFR)*

Routine flaring not only wastes valuable resources but also significantly contributes to greenhouse gas (GHG) emissions, thereby undermining national climate targets. The government's commitment through Minister Decree ESDM No.17 Tahun 2021 mandates flare gas utilization and management across the upstream sector.

Launched in 2015, the ZRF Initiative commits governments and oil companies to ending routine flaring by 2030. Gas flaring is the 160-year-old industry practice of wastefully burning, rather than

they were selected and applied in specific field environments. Given the uniqueness of upstream oil and gas operations in Indonesia—particularly their geographic dispersion, regulatory variability, and infrastructure limitations—a single-case embedded design offers a focused yet multi-dimensional analysis.

The case study approach is complemented by triangulation of data sources to enhance credibility and reduce bias. Four principal types of data were utilized: 1-Internal project data and operational performance metrics from Pertamina's

Subholding Upstream (SHU) operation, particularly from the Offshore North West Java (ONWJ) Bravo and Zulu Flow Station projects. 2-Government regulations and policy documents, including ESDM Ministerial Decrees No. 17/2021 and No. 30/2021. 3-International benchmarking from secondary literature, notably from the World Bank's Global Gas Flaring Reduction Partnership (GGFR) and the International Energy Agency (IEA). 4-Technical specifications and cost-benefit analyses of implemented technologies, such as Extended Vacuum Entrainment (EVE) ejectors, microturbine systems, and small-scale LNG units.

This methodological framework enables both descriptive and evaluative insights. Comparative analysis of regulations supports the identification of enabling policy conditions. Thematic coding of technical project data helps to distil best practices and operational challenges. Meanwhile, economic evaluation models were used to assess project feasibility based on capital expenditure (CAPEX), payback period, and operational savings.

The selected methodology also facilitates a theory-informed discussion, grounded in the Porter Hypothesis and transition theory, to interpret findings in light of policy-driven innovation and energy system transformation.

The Porter Hypothesis, proposed by Michael E. Porter in 1991, argues that well-designed environmental regulations can stimulate innovation and enhance competitiveness, rather than hinder it. Contrary to the traditional view that environmental regulations are costly and reduce efficiency, the hypothesis suggests that stringent but flexible regulations can: 1-Encourage innovation in cleaner and more efficient technologies, 2-Improve resource productivity, 3-Lead to win-win outcomes: better environmental performance and increased profitability (Porter & Linde, 1995).

Transition Theory, or Sustainability Transitions Theory, refers to the long-term, multi-level, and multi-actor processes through which socio-technical systems (like energy, transport, agriculture) shift toward more sustainable configurations. The theory is central to sustainability science and energy policy research. The most well-known model is the Multi-Level Perspective (MLP) by Geels [8], which describes three levels: 1-Niche innovations (small-scale, experimental solutions), 2-Socio-technical regime (dominant practices, regulations, infrastructure), 3-Landscape (external factors like global climate pressure, geopolitics) (Geels, 2002).

3. BACKGROUND: GLOBAL AND NATIONAL CONTEXTS

Routine flaring occurs when associated gas produced during oil extraction is combusted rather than utilized. While originally intended as a safety measure or due to a lack of infrastructure, flaring has persisted due to poor economic incentives and minimal penalties in developing economies.

Globally, countries such as Norway and Canada have implemented strict regulations and flaring reduction incentives. Norway's Petroleum Safety Authority, for example, mandates gas re-injection or market utilization, resulting in flaring rates below 2%.

Indonesia, by contrast, still flares millions of standard cubic feet per day (MMSCFD). Regulation ESDM No.17/2021 defines permitted flare types and sets limits for routine flaring, requiring operators to reduce it below 2% of daily feed gas for gas fields and 2 MMSCFD for oil fields. Ministerial Regulation No.30/2021 further outlines procedures for allocation, utilization, and pricing of flare gas, enabling monetization.

4. ZERO ROUTINE FLARING INITIATIVE: GOALS AND FRAMEWORK

The World Bank's Zero Routine Flaring (ZRF) Initiative, launched in 2015, has provided a global

framework for governments and oil producers to phase out routine flaring by 2030. Pertamina Holding (PTM), as Indonesia's national energy company, officially adopted the initiative at COP29. This move signifies not just alignment with global best practices but also commitment to the nation's broader decarbonization strategy.

The ZRF Initiative's primary goal in the Indonesian context is to eliminate the routine flaring of associated gas across upstream operations by 2030. This involves reducing emissions from flaring, improving energy efficiency, and enabling gas recovery and utilization. These objectives are embedded within national energy and environmental policies such as the National Energy Grand Strategy (GSEN) and Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement.

To operationalize these goals, PTM has outlined several strategic actions, including investments in flare gas capture infrastructure, deployment of real-time flare monitoring systems, and integration of low-carbon technologies. These efforts are aimed at transforming upstream facilities into energy-efficient operations capable of reusing or monetizing previously wasted gas resources. According to the IEA (2023), such integrated approaches are crucial for balancing production targets with emission reduction commitments in emerging economies.

5. CHALLENGES AND OPPORTUNITIES IN IMPLEMENTATION

Implementing ZRF in Indonesia presents both logistical and economic challenges. First, infrastructure constraints remain a major barrier. Many producing fields, particularly in offshore and remote inland areas, lack access to processing or transportation infrastructure. Building gas pipelines or LNG processing units in these locations can be capital-intensive and logistically complex.

Second, the economic viability of flare gas recovery is limited by the relatively low volume and low pressure of associated gas in some fields. The upfront cost for installing gas recovery systems is significant, especially for smaller producers. As highlighted by the O&G Journal (2022), economic disincentives often result in delayed investments in flare capture solutions, particularly in fields nearing the end of their productive life.

Technological gaps also impede widespread adoption. While advanced technologies such as gas reinjection, microturbines, and EVE ejectors are now available, their integration into aging infrastructure is not always feasible. Additionally, regulatory fragmentation and lengthy permitting processes may delay project execution.

However, these challenges are counterbalanced by emerging opportunities. The Indonesian government has enacted enabling regulations, including ESDM Decrees No. 17/2021 and No. 30/2021, which provide a legal framework for flare gas allocation, pricing, and monetization. Furthermore, industrial gas demand remains strong, providing a clear market for captured flare gas. According to BPS (2022), the industrial sector accounts for over 30% of national gas consumption.

International cooperation also presents an opportunity. Climate finance instruments such as the Green Climate Fund and technical assistance programs from development agencies can support flare gas reduction projects through concessional funding and risk-sharing mechanisms.

5.1. Challenges

Infrastructure limitations: Many producing fields are in remote or offshore locations, lacking pipeline or processing infrastructure. Economic disincentives: Historically, flaring has been a low-cost disposal method compared to investment in gas capture and utilization. Technological

gaps: Deployment of advanced flare gas recovery systems requires significant upfront investment and operational expertise.

5.2. Opportunities

Flared gas monetization: Associated gas can be repurposed for small-scale LNG, microturbines for power, or EOR applications. International cooperation: Climate finance and technology transfer initiatives offer support for flare reduction projects. Policy and regulation: The regulatory environment is increasingly supportive, with clear frameworks for flare gas management and utilization (Figure 2).

Thus, the combination of government policies that support the monetization of flared gas and high demand from the industrial sector plays a significant role in increasing the utilization of flared gas in Indonesia in 2022.

5.3. Key Changes in Regulation Number 30 of 2021 Compared to Regulation 32 of 2017

Buyers of Flared Gas: Limited to business entities with Processing and/or Natural Gas Trading Business Licenses (government agencies removed). Procedures for Determining Allocation, Utilization, and Price: Buyers and KKKS negotiate based on commercial principles, then submit a

Lapangan	Lokasi	Jenis Lapangan	Fasilitas Produksi	Koordinat Flare Stack		Produksi		Reinjeksi	Pemanfaatan		Pembakaran Gas Suar							Komposisi Gas Suar	Keterangan
				LS	BT	Minyak	Gas				Rutin	Keselamatan	Non Rutin	Darurat	Pengotor	Tambahan Fuel Pembakaran Gas Pengotor	Terkendala Komersialisasi		
						(BOPD)	(MMSCFD)	(MMSCFD)	(MMSCFD)	Persentase	(MMSCFD)	(MMSCFD)	(MMSCFD)	(MMSCFD)	(MMSCFD)	(MMSCFD)	(MMSCFD)		
Lap A	Onshore/ Offshore	Minyak/ Gas	GS A	LS1	BT1														
				LS2	BT2														
				LS3	BT3														
			GS B																

Figure 2. *Indonesia's Regulation for Flare Gas Management (Source: ESDM No.17/2021)*

The increase in the use of flare gas in Indonesia in 2022 can be attributed primarily to the government's efforts to facilitate the process of monetizing flare gas. Through the issuance of Minister of Energy and Mineral Resources Regulation Number 30 of 2021, the government stipulates procedures for determining the allocation, utilization, and price of flare gas in upstream oil and gas business activities. This regulation is designed to accelerate and facilitate the process of monetizing flare gas, thereby encouraging increased utilization.

In addition, the industrial sector is a major contributor to the utilization of natural gas in Indonesia. As of September 2022, gas utilization by industry reached 29.73% of the total national gas utilization, making it the sector with the largest gas consumption compared to other sectors.

proposal to SKK Migas/BPMA, which forwards it to the Minister for approval. Delivery Point: No specific regulation on the delivery point. Price: Determined through agreements between buyers and KKKS based on commercial principles (fixed maximum price for government institutions removed). Flare Potential Information: The Minister (via the Director General of Oil and Gas) publicly provides flare gas potential data from SKK Migas/BPMA. Transitional Provisions: Covers only signed sale and purchase agreements and previously set gas prices.

Flaring of Flare Gas, as referred to in Article 2, paragraph (2) letter b, is carried out by Contractors or Business Entities Holding Processing Business Permits in the case of:

a. Routine Flare Gas Burning; this will be

zeroed in the 2030 target.

b. Non-Routine Flare Gas Burning;

c. Flare Gas Burning for Safety;

d. Flare Gas Burning from low-pressure gas and/or Flare Gas burning with an average Impurity Gas content of more than 50% (fifty percent) moles, which, based on technical and economic studies, has not or cannot be utilized;

e. Conditions or events or series of events due to failure of equipment or installation systems that can threaten or endanger the safety of human life, both workers and/or the surrounding community or can cause environmental damage, damage to public facilities or production assets/facilities, and social impacts on the community (emergency conditions).

f. Flare Gas Burning from additional gas as fuel for Flare Gas Burning, containing Impurity Gas to maintain the flame; and

g. Flare Gas from natural gas production that is experiencing commercialization constraints. à See article 10 (Determination by the Director General of Oil and Gas)

Flare Gas Management, according to ESDM Regulation Number 17 of 2021, is divided into two, namely burning and utilization. Regarding burning, it consists of routine, non-routine, and safety. Routine burning is the burning of flare gas under normal conditions, where geological conditions do not allow for gas reinjection, there are no facilities for gas reinjection, or there is no use of flare gas for personal or other needs. Routine burning can be carried out on the condition that it does not exceed 2% of the daily volumetric flow rate of feed gas for natural gas fields and a daily average in 6 months of 2 MMSCFD for oil fields.

Flaring for safety is the burning of flare gas in order to ensure the safety of oil and gas operations. Meanwhile, non-routine burning is the burning of flare gas other than routine flare gas burning and flare gas burning for safety.

6. UPSTREAM OPERATION DECARBONIZATION STRATEGIES

To meet the ambitious goals of the ZRF initiative, PHE has implemented a multi-pronged decarbonization strategy that encompasses institutional alignment, technology deployment, and renewable integration.

Institutionally, PHE has centralized upstream decarbonization efforts. This includes coordinating across subsidiaries to align project planning with Net Zero Emissions goals by 2060. These efforts are supported by internal technical standards that incorporate ESG (Environmental, Social, and Governance) metrics into project assessments.

From a technological standpoint, PHE has focused on enhancing gas utilization. In fields where reinjection is feasible, such as in mature reservoirs, associated gas is reinjected to maintain reservoir pressure and enhance oil recovery. In areas where gas transportation is viable, PHE has invested in pipeline infrastructure to transport gas to processing facilities or end-users.

Small-scale LNG projects have also been deployed in remote regions, allowing for the monetization of stranded gas. These modular systems convert flare gas into transportable LNG, which is then used for industrial applications or off-grid power.

Innovative technologies have been introduced, most notably the Extended Vacuum Entrainment (EVE) ejector system implemented in 2023 at ONWJ's Bravo Field. This system utilizes high-pressure motive gas to entrain and compress low-pressure gas that would otherwise be flared. Field data showed a 30% increase in gas utilization following its installation, demonstrating both environmental and economic value.

Real-time flare monitoring systems, integrated

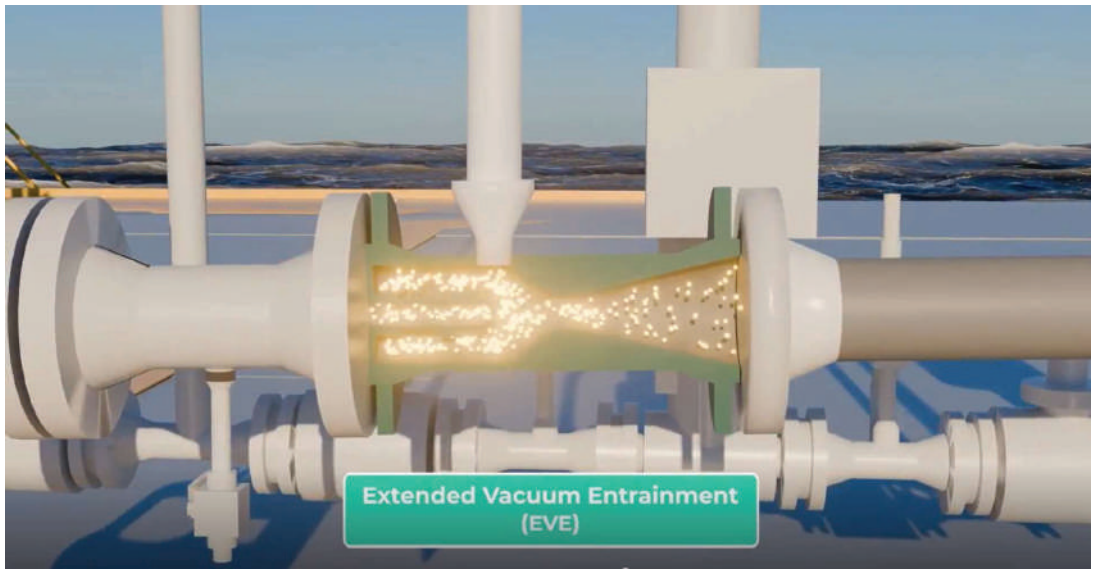


Figure 3. *EVE Ejector Schematic (Source: Pertamina)*

with SCADA platforms, allow operators to track flare volumes and system performance continuously. These systems support proactive maintenance and optimization, reducing the likelihood of unplanned flaring events.

PHE has also prioritized renewable integration. Photovoltaic systems have been installed at select upstream facilities, and microturbine systems powered by recovered gas have been deployed to replace diesel generators. These solutions not only reduce emissions but also enhance energy security for remote operations.

6.1. Gas Utilization Projects

SHU's gas utilization initiatives include: Gas reinjection for EOR: Enhances oil recovery while minimizing flaring, Pipeline development: New infrastructure connects remote fields to markets, and Small-scale LNG plants: Converts flared gas to LNG for transport and use.

6.2. Technology Adoption

SHU has deployed advanced solutions, including: Flare gas recovery systems: Captures flare gas for reuse, Real-time flare monitoring and optimization: Enhances operational control., Extended Vacuum Entrainment (EVE) ejectors: First implemented in 2023 at ONWJ's Bravo Field, EVE ejectors use high-pressure gas to recover low-pressure gas that would otherwise be flared (Figure 3).

6.3. Renewable Energy Integration

PHE is expanding renewable energy deployment at its upstream facilities, including solar and microturbine systems powered by recovered gas (Figure 4).

7. PROJECT CASE STUDIES

7.1. ONWJ Bravo Field EVE Project

In 2023, PHE ONWJ successfully implemented the EVE ejector at Bravo Field. The system recovers low-pressure associated gas, reducing flaring and boosting gas utilization by 30%. This project demonstrated technical feasibility and set a precedent for similar installations across Pertamina assets.

7.2. Small-Scale LNG Development

Pertamina initiated small-scale LNG production from associated gas in remote fields. These plants supply gas to local industry and power generation, reducing reliance on diesel and cutting emissions.

7.3. Microturbine Deployment

Microturbines fuelled by flare gas have been installed at select sites, providing reliable power for operations while eliminating routine flaring.

PHE ONWJ has implemented energy-efficient technologies, including the installation of mini gas compressors, to enhance operational efficiency and reduce environmental impact. The retrofit involved replacing the compressor at the Zulu Flow Station with a mini compressor, representing an investment of USD 1 million and achieving a payback period of just 1.5 years. The installation of this compressor is done by utilizing flare gas that has been discarded to reduce pressure converted into fuel gas to drive the compressor itself. The installation of this tool can eliminate dependence on diesel fuel that has had to be sent from the mainland. The existing Turbine Gas Generator Set can generate electricity with a capacity of 2.5 MW. From the implementation of this activity, the savings achieved are 23,149.87 GJ, or equivalent to USD 580,000 per year.

8. CONCLUSION AND PATH FORWARD

To accelerate progress toward ZRF by 2030, a number of strategic actions are recommended. First, SHU should scale successful pilot projects across all its upstream assets, focusing on fields with high flaring volumes and favourable technical conditions. Scaling requires not only capital investment but also a coordinated strategy for technology transfer and operator training.

Second, regulatory harmonization is essential. While current regulations provide a strong foundation, improved coordination among SKK Migas, EBTKE, and regional authorities can reduce permitting delays and clarify technical standards. A dedicated flare gas task force within these agencies may streamline policy execution.

Third, SHU should further integrate digital tools for flare monitoring, emissions tracking, and predictive maintenance. Advances in data analytics, machine learning, and automation offer new opportunities for operational efficiency.

Fourth, access to international climate finance should be actively pursued. Instruments such as concessional loans, blended finance, and carbon credit schemes can mitigate the high upfront costs of flare gas infrastructure. Collaborations with organizations such as the World Bank, ADB, and UNDP could be instrumental in this regard.

Finally, increased collaboration with international technology providers and research institutions is encouraged. These partnerships can facilitate the transfer of cutting-edge technologies, co-develop innovative solutions, and ensure that Indonesian operators remain at the forefront of sustainable oil and gas practices.

Indonesia's ZRF initiative is both a necessity and an opportunity. PHE's leadership, supported by

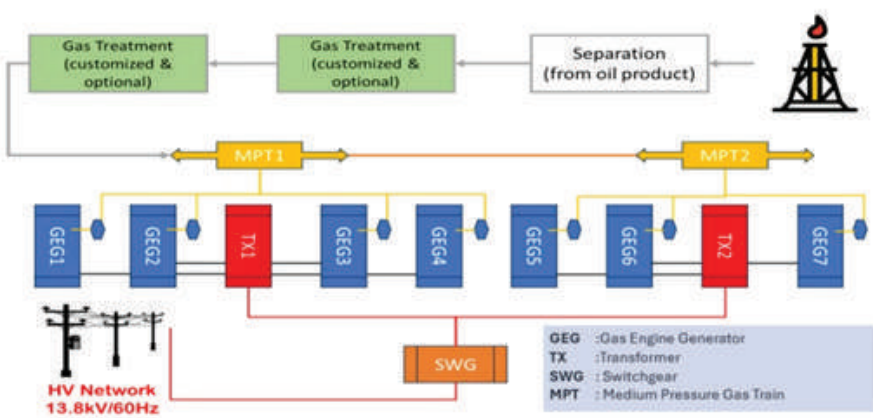


Figure 4. Microturbine Flare Gas to Power Schematic (Source: Pertamina)

regulatory momentum and evolving technologies, positions Indonesia to meet its decarbonization goals while maximizing energy value. Scaling pilot projects, embracing digital tools, and aligning with global practices will be key to ensuring sustainable and efficient upstream operations.

This study contributes to the regional discourse on flare gas management by validating technologies and strategies with measurable field outcomes. Further research is encouraged to develop predictive models for flare gas economics in Southeast Asia.

9. ACKNOWLEDGMENT

The authors thank the Indonesian Government for policy leadership, the GGFR initiative for data transparency, and PHE's internal technical teams for innovation and field support.

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TENTANG PENULIS



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REVITALIZING MARGINAL OFFSHORE WELLS THROUGH PRESSURE OPTIMIZATION: THE LIMITLESS METHOD

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ABSTRACT

Mature offshore production facilities often experience output decline not because of reservoir depletion but due to elevated surface backpressure that prevents viable wells from flowing. These latent productive wells remain shut-in behind infrastructure constraints rather than geological limits. This study presents the LIMITLESS method (Lowering Infrastructure Management and Integrated Throughput Enhancement for Sustainable Systems), a low-CAPEX, multi-phase strategy that reduces operating pressure and restores well deliverability using existing assets. Implemented across two offshore fields, the program successfully reduced suction pressure from 140 psig to 90 psig, reactivated shut-in wells, and achieved incremental gains of 355 BOPD and 7.98 MMSCFD.

Economic evaluation indicated a total value creation of IDR 419.52 billion (≈ USD 26 million), comprising realized gains of IDR 373.38 billion from 19 September 2023 to September 2025 and projected gains of IDR 46.14 billion through the end of 2025. The analytical framework integrated Failure Mode and Effect Analysis (FMEA) for risk identification with AHP–TOPSIS for decision prioritization, supported by process and network simulations (HYSYS, Nodal Analysis, Softmap). The hybrid FMEA–MCDM approach ensured that engineering interventions directly targeted the dominant risks, high backpressure and reduced fluid throughput, identified during risk screening.

The findings demonstrate that systematic pressure optimization within existing infrastructure can safely revive shut-in wells, enhance compressor stability, and extend field life while aligning with corporate sustainability and flaring-reduction goals.

1. INTRODUCTION

Mature offshore assets contribute a significant portion of global oil and gas supply but are increasingly constrained by aging infrastructure and rising operational inefficiencies. As production declines, compressors, separators, and pipelines that were originally designed for high-pressure conditions impose excessive backpressure on connected wells. This artificial resistance causes a portion of the well population to become shut-in, even though sufficient reservoir drive remains. The result is a paradox of underutilized subsurface

potential coexisting with surface systems operating far below economic optimum [1–3].

In the past two decades, the industry's focus on brownfield optimization has intensified as operators face stricter environmental standards, higher marginal costs, and limited opportunities for new developments. According to the International Energy Agency (IEA 2024), more than 60 percent of global offshore production now originates from fields older than twenty years, with an estimated 15–25 percent of installed capacity affected by surface bottlenecks rather than reservoir depletion [5]. Consequently, low-CAPEX interventions that maximize existing assets have become central to sustaining output while aligning with decarbonization targets such as the World Bank's *Zero Routine Flaring by 2030* initiative [7].

Numerous strategies have been proposed to mitigate backpressure and revive declining systems. Traditional approaches include installing additional booster compressors, rerouting flowlines, or developing satellite gathering facilities. While technically effective, these methods often require significant capital expenditure and extended shutdowns that may not be economically feasible for marginal fields [4,8–10]. Recent studies emphasize that re-engineering existing compression and separation configurations can yield similar productivity gains at a fraction of the cost. Cheng et al. (2021) and Ibrahim et al. (2023) demonstrated that staged pressure reduction, combined with compressor re-balancing, can increase throughput by 10–20 percent without new installations [18–20].

Beyond technical interventions, a paradigm shift is emerging toward risk-informed and sustainability-aligned optimization. The integration of Failure Mode and Effect Analysis (FMEA) with multi-criteria decision-making (MCDM) frameworks allows operators to quantify operational risks and prioritize interventions that deliver both production and sustainability value [11–15]. Such hybrid methodologies strengthen decision transparency, linking reliability, cost, and environmental performance within a single analytical structure.

Within this context, the present study introduces the **LIMITLESS method** (Lowering Infrastructure Management and Integrated Throughput Enhancement for Sustainable Systems), a systematic approach for reactivating shut-in wells through controlled pressure reduction in existing facilities. The program was implemented across two offshore fields in Indonesia and designed to achieve three objectives: (1) reduce suction pressure while maintaining compressor stability, (2) restore flow from wells previously constrained by high backpressure, and (3) quantify the resulting value creation and emission benefits. The method integrates process simulation, risk assessment, and structured decision analysis to transform theoretical pressure-optimization concepts into a validated operational framework.

By detailing both the analytical foundations and field implementation outcomes, this paper aims to contribute practical insights for operators seeking cost-effective production recovery pathways in mature offshore environments. The findings further demonstrate how engineering innovation can directly support corporate commitments to reliability, safety, and sustainable energy transition.

2. LITERATURE REVIEW

2.1 Backpressure and Flow Potential

Backpressure represents the cumulative resistance imposed by surface facilities on well outflow, encompassing frictional losses, separator and compressor suction pressures, and control-valve configurations. Its effect on well productivity has been extensively studied in petroleum-engineering literature, forming a cornerstone of inflow–outflow performance analysis. The classical Rawlins–Schellhardt

(1935) backpressure equation describes the non-linear relationship between gas-flow rate and flowing pressure, establishing that deliverability decreases exponentially as surface pressure approaches bottomhole pressure [1]. Subsequent developments, such as the Cullender–Smith (1956) [2] and Vogel (1968) [3] correlations, extended this concept to multiphase systems and depleted reservoirs, enabling engineers to quantify production potential under variable surface conditions.

Modern studies confirm that even modest reductions in surface pressure can lead to disproportionate increases in well deliverability, particularly in mature assets with sufficient reservoir energy. Spyrou (2012) and Rojas et al. (2019) reported that production enhancement through pressure optimization requires minimal intervention when supported by accurate system modeling and wellbore-hydraulics validation [18, 19]. In offshore brownfields, however, surface backpressure is rarely an isolated variable; it arises from interconnected systems including compressors, slug catchers, separators, and network headers originally designed for higher production rates and reservoir pressures. As field conditions evolve, these design pressures become operational bottlenecks. Studies by Cheng et al. (2021) and Ibrahim et al. (2023) identified compressor-suction setpoints and pipeline-network resistance as dominant contributors to artificial shut-ins, accounting for a significant fraction of lost production capacity in mature fields [18–20].

For brownfield operators seeking low-cost recovery options, pressure optimization represents a technically viable and economically efficient intervention. The key challenge lies in identifying the optimal degree of pressure reduction that reactivates shut-in wells while maintaining compressor stability and process integrity. This balance requires integrating production-system modeling, facility adequacy checks, and risk-informed decision-making. These foundations underpin the development of the LIMITLESS framework in this study, which applies multi-phase simulation and structured risk assessment to translate theoretical backpressure principles into operational recovery strategies.

2.2 Compressor Configuration and Efficiency

Gas-compression systems are among the most critical and energy-intensive components in offshore production facilities. Their configuration strongly influences overall system pressure, flow distribution, and energy efficiency. In mature brownfields, compressors originally designed for higher suction pressures and throughput often operate far below their design envelopes, leading to off-design performance, increased recycle flow, and higher energy consumption. As a result, the relationship between compressor configuration and facility backpressure becomes a dominant factor in production decline [8–10].

Early research by Meher-Homji (1990) [9] and Aretakis et al. (2012) [8] established that compressor fouling and mismatched operating envelopes can significantly reduce effective head if not periodically optimized. Subsequent works such as Gesser et al. (2022) [18] emphasized adaptive control and performance mapping to maintain optimal compressor efficiency under fluctuating field conditions. Configuration optimization may involve re-staging, series–parallel re-arrangement, or bypass modifications to align head and flow with current operating requirements. Cheng et al. (2021) and Ibrahim et al. (2023) demonstrated that converting twin parallel compressors into a hybrid series configuration improved suction-pressure control and reduced recycle activity in offshore gas plants [18–20].

Digital performance monitoring further enhances compressor management. Machine-learning-based fouling detection, model-predictive control, and virtual sensing of surge margins

have been integrated into modern optimization frameworks [18–20]. However, successful implementation requires accurate process modeling and awareness of how compressor behavior interacts with downstream equipment, particularly separators and gas-lift systems. If suction pressure is lowered too aggressively, liquid carry-over or unstable operation may occur. Therefore, compressor optimization must be coupled with risk assessment and dynamic simulation to ensure mechanical integrity and process stability.

The literature thus converges on a common principle: compressor configuration and efficiency optimization form the operational lever through which backpressure can be managed safely and economically. For brownfield operators, these insights support the transition from design-setpoint operation toward adaptive, data-driven performance management. This principle underpins the LIMITLESS approach developed in the present study.

2.3 Risk-Informed Decision Framework

In managing mature offshore production systems, facility optimization is most effective when guided by quantitative risk assessment. Several authors have demonstrated that traditional debottlenecking or compression-reconfiguration efforts often overlook systemic-risk interdependencies that influence reliability and production outcomes [11–15]. Integrating Failure Mode and Effect Analysis (FMEA) with multi-criteria decision-making (MCDM) techniques such as AHP–TOPSIS has therefore gained increasing relevance in oil-and-gas engineering [11–15].

Within this study, FMEA was first employed to systematically screen process and operational risks associated with declining throughput. The analysis provided a structured means to rank potential failure modes according to their severity, occurrence, and detectability, allowing the team to identify the most significant constraints affecting production continuity. Elevated surface pressure and reduced fluid rate emerged as the most dominant operational risks. These findings subsequently served as key input criteria for the AHP–TOPSIS stage, ensuring that the decision-making process addressed verified, high-impact risks rather than subjective assumptions.

This risk-informed prioritization aligns with operational-excellence principles, where technical decisions are quantitatively justified through traceable, data-driven frameworks. Previous applications of FMEA–AHP or FMEA–TOPSIS hybrids in offshore reliability and process-optimization contexts have shown similar benefits, improving transparency and stakeholder confidence in engineering decision-making [13–15].

2.4 Sustainability and Operational Decarbonization

Sustainability considerations have become integral to brownfield-optimization strategies, reflecting the global shift toward low-carbon operations. The oil-and-gas sector—responsible for nearly 15 percent of global energy-related greenhouse-gas emissions—is under increasing pressure to reduce its operational footprint without compromising energy security [5–7]. A significant share of these emissions originates from combustion-based processes, particularly gas compression, flaring, and power generation. According to the *Global Methane Tracker 2024* [5], approximately 139 billion m^3 of gas was flared worldwide in 2023, releasing roughly 250 million tons of CO_2-equivalent.

Brownfield decarbonization depends not only on replacing fuels or electrifying operations but also on improving system efficiency through optimization of pressure management and energy use. Studies compiled by IPIECA (2021) [16] and BSEE (2017) [17] show that optimization

and reconfiguration programs can significantly reduce flaring and improve energy intensity. These findings reinforce the view that sustainable operation is inherently linked to process reliability and control, not merely to emissions offsets.

From a lifecycle perspective, reducing the need for new compressor installations or large-scale retrofits also prevents the embodied emissions associated with manufacturing, transport, and offshore installation activities [17]. The avoided carbon footprint from deferred fabrication and mobilization can be equivalent to several thousand tons CO_2-equivalent per project, providing environmental value beyond operational savings. This aligns with corporate decarbonization pathways and national commitments such as Indonesia's Enhanced NDC (2022), which emphasizes energy-efficiency improvement and methane-reduction measures.

The LIMITLESS framework directly contributes to these sustainability objectives by re-engineering existing assets rather than adding new hardware. Through controlled pressure reduction, it minimizes recycle and flare events, enhances compressor efficiency, and prolongs equipment life. Consequently, the method links short-term production recovery with long-term emission reduction, demonstrating that operational optimization and sustainability can be mutually reinforcing goals within mature offshore developments.

3. METHODOLOGY

3.1 Overview of the Study Approach

The research followed a structured, multi-stage methodology designed to diagnose production constraints, prioritize improvement options, and validate operational changes through simulation and phased field implementation. The sequential workflow consisted of five main stages:

1. Data acquisition and performance diagnosis,
2. Risk screening through Failure Mode and Effect Analysis (FMEA),
3. Decision evaluation using Analytic Hierarchy Process (AHP) and TOPSIS,
4. Dynamic simulation and adequacy checks, and
5. Controlled field execution with monitoring and feedback.

This staged approach ensured that each engineering decision was grounded in quantitative evidence and traceable risk analysis, consistent with the frameworks proposed by Hwang and Yoon [11], Saaty [12], and later adapted to reliability engineering by Kutlu and Ekmekçi [13] and Shafiee et al. [14].

3.2 Field Description and Baseline Conditions

The study was conducted in Offshore Field X and Field Y, two interconnected brownfield facilities located in the western part of Indonesia's continental shelf. Both fields are tied to a central processing platform equipped with dual gas-turbine compressors (GTC-624 and GTC-623) originally configured in parallel. The design assumed suction pressures between 130 and 150 psig and total gas throughput exceeding 80 MMSCFD.

After more than a decade of operation, reservoir pressure declines and changing gas–liquid ratios led to progressively lower wellhead flowing pressures. As system backpressure remained high, several wells were unable to flow and were eventually shut in. Operational monitoring also indicated increasing compressor recycle frequency and higher energy intensity, confirming off-design operation consistent with findings from Aretakis et al. [8] and Meher-Homji [9]. These observations formed the technical basis for investigating pressure optimization within existing infrastructure.

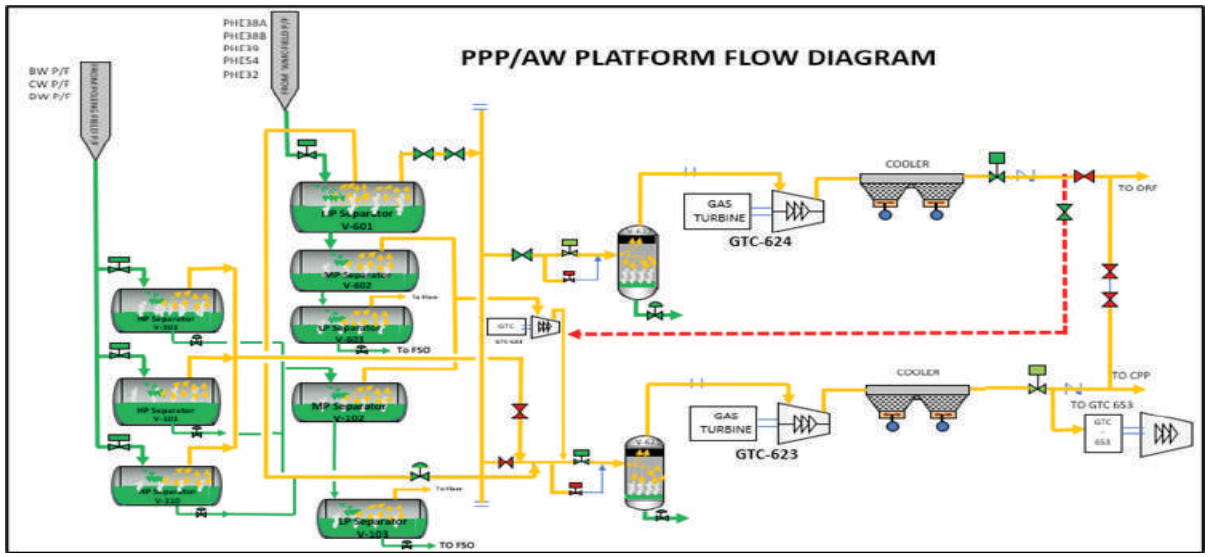


Figure 1. *Simplified Flow Diagram*

3.3 Data Collection and Diagnostic Analysis

A comprehensive data-gathering phase preceded analytical modeling and simulation. The following datasets were collected:

- **Process and equipment data:** suction/discharge pressure trends, compressor performance logs, and separator operating envelopes.
- **Production data:** daily oil, gas, and water rates for all active and shut-in wells.
- **Maintenance and reliability data:** vibration alarms, instrumentation drift records, and corrective maintenance frequencies.

All datasets were validated through cross-checks between the historian database and manual operations logs. Statistical smoothing and outlier removal were applied to eliminate transient upsets not representative of steady-state operation. The validated dataset provided a robust foundation for the quantitative risk and decision analyses recommended in similar optimization frameworks [13–15].

3.4 Risk Identification through FMEA

A Failure Mode and Effect Analysis (FMEA) was used to systematically identify and rank potential causes of production loss, following the standard methodology outlined by Shafiee et al. [14]. Each failure mode was assessed using three classical parameters, namely, severity (S), occurrence (O), and detection (D), to compute a Risk Priority Number (RPN = S × O × D).

The analysis team included representatives from process, mechanical, operations, and instrumentation disciplines to ensure cross-functional objectivity. The FMEA matrix encompassed ten potential failure modes, including compressor surge, separator carry-over, instrumentation drift, and high suction-pressure operation. Summation of RPN values revealed that surface-pressure management and declining fluid throughput were the two most dominant risks, representing approximately 80 percent of total weighted risk. These results formed the quantitative foundation for the subsequent decision-analysis phase using AHP–TOPSIS [11–13].

Table 1. *FMEA Workflow*

Failure Mode & Effect Analysis								
No.	Deskripsi Proses	Failure Mode	S	O	D	Risk Priority Number (RPN)	% Rel	% Kum
A	Setting operasi pada tekanan tinggi	Terjadi akumulasi tekanan dan fluida baik di pipeline maupun vessel sehingga menyebabkan backpressure ke sumuran.	8	9	5	360	49%	49%
B	Penurunan laju alir fluida	Dengan terus diproduksikannya sumur menyebabkan jumlah aliran fluida dari sumur terus berkurang, sehingga akan mempengaruhi jumlah aliran fluida yang diproduksi ke Surface Facilities. Mengakibatkan Laju alir produksi minyak & gas akan menurun.	5	9	5	225	31%	80%
C	GTC beroperasi single run	GTC akan mengalami kerusakan yang disebabkan oleh beban volum yang lebih besar dari kapasitasnya.	8	4	4	128	17%	97%
D	Tidak ada eksplorasi sumur baru	Tidak ada penambahan minyak dan gas untuk menekan laju natural decline.	1	10	2	20	3%	100%

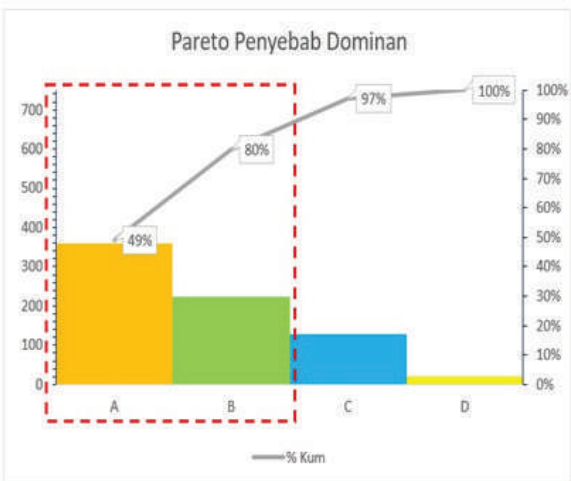


Figure 2. *Pareto Distribution*

3.5 Decision Prioritization through AHP–TOPSIS

Building upon the FMEA outputs, three technical alternatives were formulated:

1. Renting additional compressor units,
2. Re-staging existing compressors, and
3. Reconfiguring the system to lower operating pressure (LIMITLESS option).

The decision process was conducted using the **Analytic Hierarchy Process (AHP)** to establish the relative importance of evaluation criteria, **cost, duration, effort, and operational impact**, as illustrated in *Figure 3*. The hierarchical structure (goal–criteria–alternatives) reflects the objective of identifying the most effective and efficient method to reduce operating pressure while ensuring system stability. Each criterion was compared pairwise using the **Saaty (1–9) importance scale**, as shown in *Table 2*, and the resulting judgment matrix was verified for consistency, yielding a ratio below 0.1.

Quantitative weighting results are summarized in *Table 2*. The LIMITLESS alternative, corresponding to the **Lowering Pressure** configuration, achieved the highest total weighted score of **0.595**, significantly outperforming

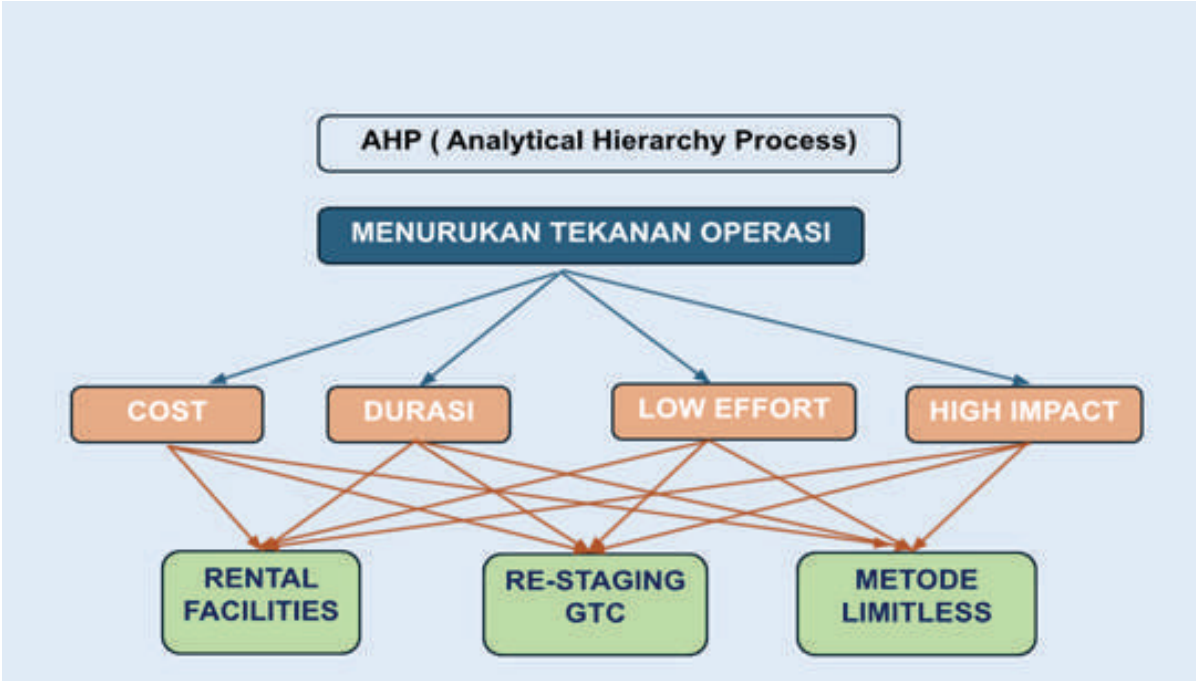


Figure 3. *Analytical Hierarchy Process*

Restaging (0.179) and **Renting (0.108)**. These results indicate that lowering pressure offers the optimal balance among low CAPEX (≈ IDR 2.2 billion), short duration (≈ two months), minimal operational effort, and high impact on production continuity.

Following AHP, the **Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)** was applied to validate the ranking consistency. Normalized decision matrices and Euclidean distances to the positive and negative ideal solutions were calculated following Hwang and Yoon's methodology [11]. The results confirmed the AHP ranking, with the LIMITLESS option exhibiting the smallest distance to the ideal solution, reinforcing its selection as the most favourable intervention.

Collectively, the AHP–TOPSIS analysis provided a quantitative and transparent framework for prioritizing technical alternatives. It ensured that the selected strategy was not only economically justified but also aligned with operational feasibility and sustainability objectives, thereby forming the analytical foundation for subsequent implementation and simulation validation stages.

Table 2. *AHP Criteria Weights and TOPSIS Ranking*

Intensitas Kepentingan	Definisi
1	Sama pentingnya dibanding dengan yang lain
3	Sedikit lebih penting dibanding yang lain
5	Cukup penting dibanding dengan yang lain
7	Sangat penting dibanding dengan yang lain
9	Ekstrim pentingnya dibanding yang lain
2, 4, 6, 8	Nilai diantara dua penilaian yang berdekatan
Resiprokal	Jika elemen I memiliki salah satu angka di atas dibandingkan elemen j, maka j memiliki nilai kebalikannya ketika dibanding dengan i

Alternative Solutions

Alternative	Cost	Durasi	Effort	Impact
Renting	300 M	2 Tahun	High	ada
Restaging	60 M	1 Tahun	High	ada
Lowering Pressure	2.2128 M	2 Bulan	Low	Tidak ada

AHP (Analitical Hierarchy Process)

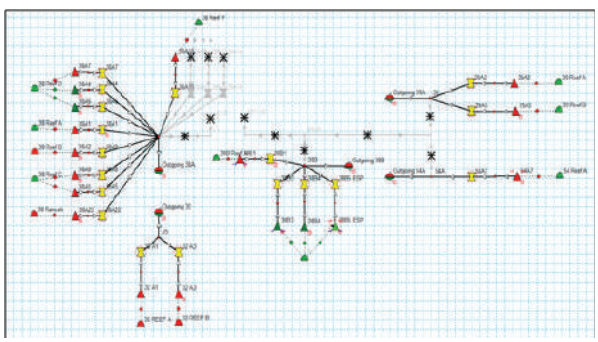
Description	Cost	Durasi	Effort	Impact	TOTAL	Rangking
Renting	0.084	0.007	0.013	0.004	0.108	III
Restaging	0.084	0.064	0.013	0.019	0.179	II
Lowering Pressure	0.390	0.064	0.108	0.033	0.595	I

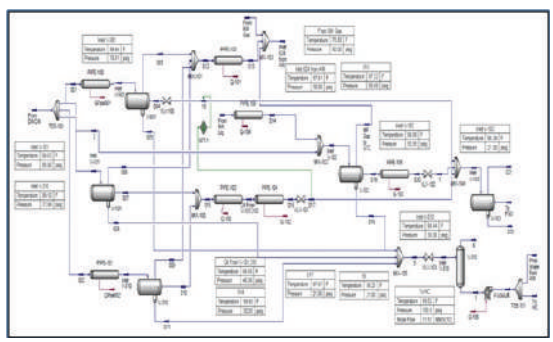
3.6 Process Simulation and Adequacy Checks

Operational feasibility was validated through integrated simulation using **Aspen HYSYS**, **SoftMap**, and **Nodal** tools. The simulation workflow included:

- Steady-state process modelling of compressors, separators, and pipelines at varying suction pressures (140, 120, and 90 psig).
- Facility adequacy checks, ensuring operation within design envelopes for pressure, temperature, and liquid-handling capacity.
- Well deliverability estimation by coupling nodal analysis with surface-network pressure profiles.
- Energy-intensity calculations to estimate compressor power versus throughput.

This combined modelling approach ensured that suction-pressure reduction would not compromise compressor surge margin or downstream process stability. The workflow follows best practices in process control and compressor optimization outlined by Rasmussen [20] and Kurz [19].





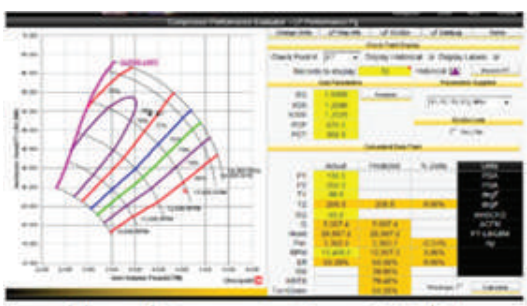


Figure 6 Compressor Curve GTC-624



Figure 7 Compressor Curve GTC-623



Figure 8 Compressor Curve GTC-653

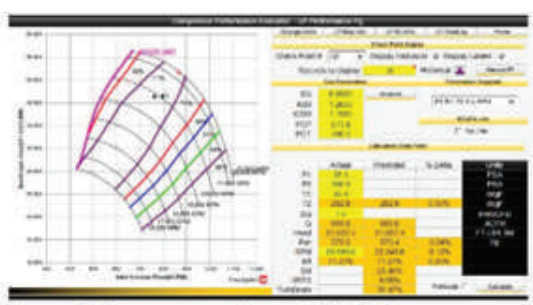


Figure 9 Compressor Curve GTC-633

Figure 4. *Integrated Simulation Framework*

3.7 Implementation Strategy

Field execution followed five sequential phases:

1. **Engineering Verification**; Validation of simulation results and HAZOP review.
2. **Pipeline Reconfiguration**; Rerouting the discharge of **GTC-624 into the suction of GTC-623** to achieve the required discharge pressure and enable stable operation under lower suction conditions.
3. **Stepwise Pressure Reduction**; Gradual lowering from 140 to 120 to 90 psig while monitoring compressor stability.
4. **Operational Monitoring**; Continuous observation of vibration, recycle activity, and flow data during stable operation.
5. **Optimization and Review**; Evaluation of performance data and integration of lessons learned for future application.

This staged implementation ensured that all risks identified in the FMEA were mitigated in real-time. The configuration change from parallel to series operation was executed under direct process control supervision, consistent with industrial best practice for series/parallel compressor management [19,20]. The methodology established a clear traceability chain from diagnostic analysis to validated field results, forming a repeatable model for other brownfield optimization programs.

4. RESULTS

4.1 Operational Performance and System Stability

The staged pressure-lowering program was implemented between September 2023 and early 2024. Suction pressure was gradually reduced from 140 psig to 120 psig and then 90 psig, following compressor adequacy verification. To enable this transition, the discharge of GTC-624 was rerouted to the suction of GTC-623 to achieve the required discharge pressure under lower suction conditions.

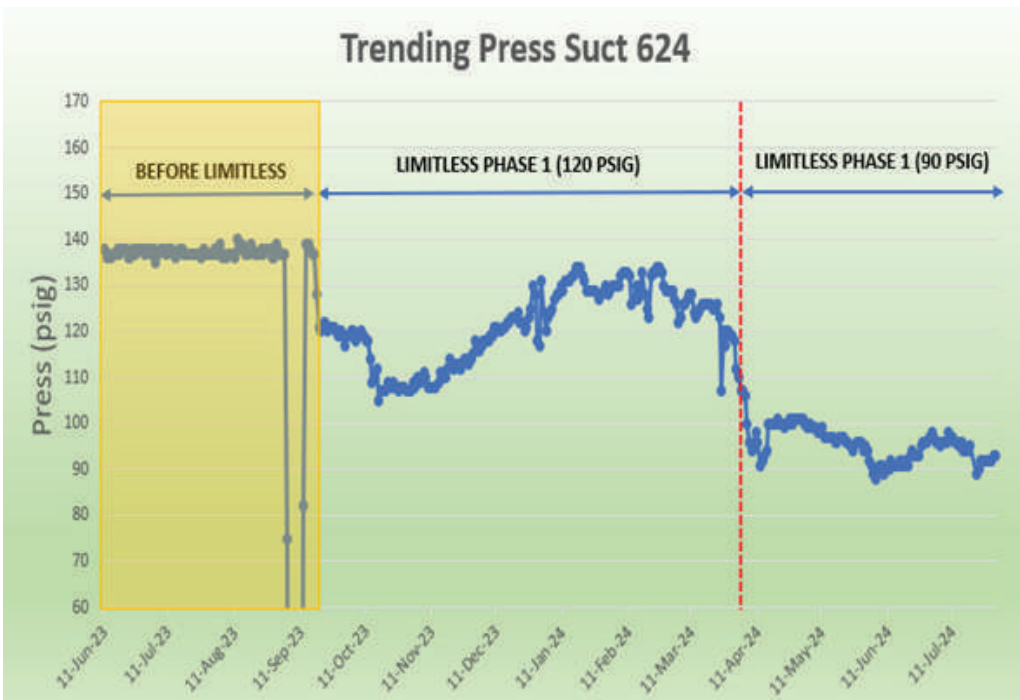


Figure 5. Pressure Before and After Optimization

This rerouting eliminated the need for additional compressor packages or capital investment. Continuous monitoring of vibration, recycle valve behaviour, and pressure differential confirmed stable operation throughout all stages. Recycle valve activity decreased, indicating improved compressor efficiency and control response. No surge events or shutdowns were recorded, and pressure fluctuations in the separation system remained within design limits.

Instrument recalibration and controller retuning further enhanced process reliability. The facility maintained steady operation with no unplanned shutdowns during the observation period, validating that pressure optimization was achieved safely and efficiently.

4.2 Reactivation of Shut-In Wells

The pressure-optimization program enabled the reactivation of several wells that had previously been shut in due to high surface backpressure. Flow restoration occurred immediately after achieving the targeted suction-pressure reduction, confirming that the wells retained sufficient reservoir energy but were restricted by facility constraints rather than subsurface limitations.

Post-startup monitoring showed stable wellhead and flowline pressures with no signs of slugging or instability. The successful reactivation verified that targeted surface optimization, rather than new compression or drilling, can economically restore flow in mature offshore environments.

4.3 Production and Throughput Gains

Following the rerouting and system optimization, combined production from both fields increased by **355 BOPD** and **7.98 MMSCFD**. This improvement reflects the recovery of previously constrained capacity and validates the effectiveness of the pressure-reduction strategy.

Field performance trends showed sustained production stability after implementation, confirming that reservoir depletion was not accelerated and that the rerouted configuration

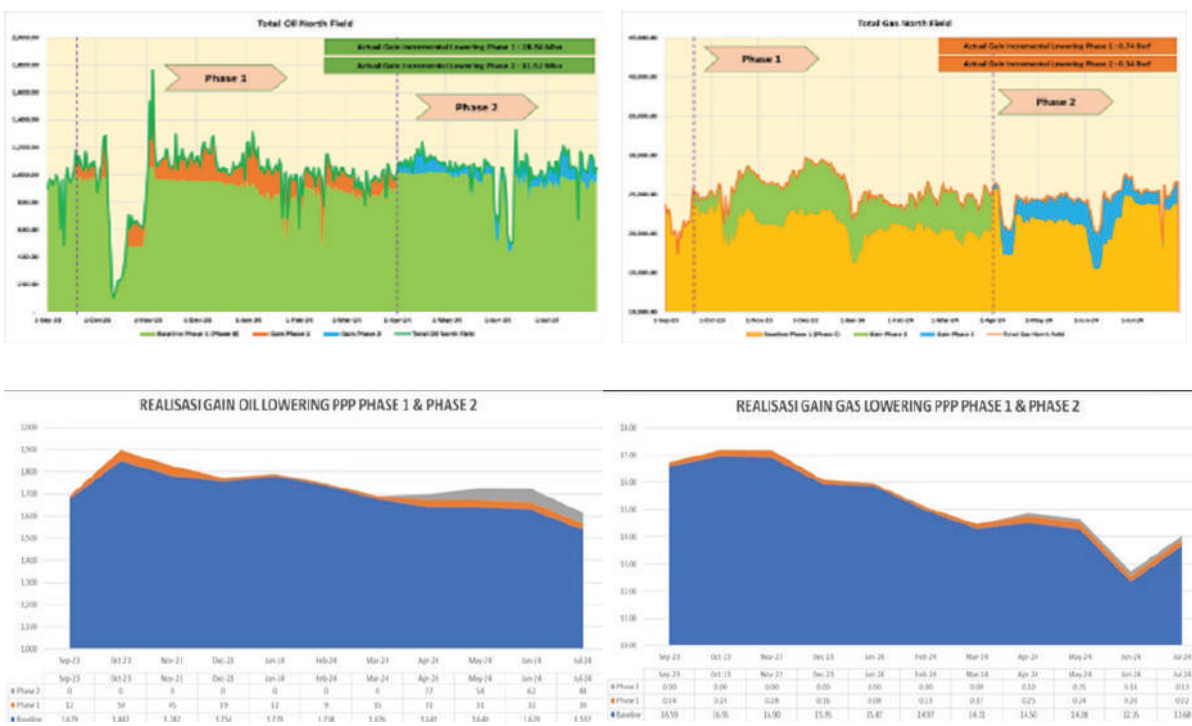


Figure 6.

provided adequate operational resilience.

4.4 Economic Evaluation

Economic analysis based on actual production and verified sales data from **19 September 2023 to September 2025**, complemented by projections through **December 2025**, indicated a total **value creation of IDR 419.52 billion (≈ USD 26 million)**. This comprised:

1. **Realized gains of IDR 373.38 billion**, measured from 19 September 2023 to September 2025.
2. **Projected gains of IDR 46.14 billion**, forecast through year-end 2025.

This value comprises incremental oil and gas revenue, reduced fuel-gas consumption due to lower recycle activity, and deferred maintenance from improved compressor reliability.

4.5 Energy and Emission Reduction

The rerouting configuration not only achieved the desired discharge pressure but also reduced energy intensity. Compressor fuel consumption declined as recycle activity fell and load distribution became more balanced, directly reducing greenhouse-gas emissions.

By avoiding new compressor installations, the initiative also prevented embodied emissions associated with manufacturing, transport, and offshore installation of new equipment. Together, the operational and embodied savings support the objectives of the **World Bank Zero Routine Flaring 2030** and **Indonesia's Enhanced NDC (2022)** commitments.

4.6 Summary of Key Outcomes

The main performance outcomes of the LIMITLESS program are summarized in Table 3. Collectively, the findings confirm that systematic pressure optimization, supported by compressor reconfiguration from parallel to series, can restore dormant capacity, improve efficiency, and generate substantial economic and environmental value without new capital investment.

5. DISCUSSION

5.1 Technical Interpretation and Validation

The reduction of suction pressure from 140 psig to 90 psig verified that the main production limitation was surface-related rather than reservoir-driven. Once the discharge of **GTC-624** was rerouted into the suction of **GTC-623**, the system achieved the required discharge pressure without new compression hardware. The rerouting increased the effective compression ratio and stabilised operation at lower suction pressures.

Field data showed smooth compressor

Table 3. *Summary of Performance Metrics*

PARAMETER	BASELINE	AFTER LIMITLESS	IMPROVEMENT
Compressor Configuration	Parallel	Rerouted (Discharge to Suction)	Reconfigured for Pressure Optimisation
Suction Pressure	140 psig	90 psig	Reduced Operating Backpressure
Incremental Oil Production	–	+355 BOPD	Restored Capacity
Incremental Gas Production	–	+7.98 MMSCFD	Restored Capacity
Value Creation (IDR)	–	419.52 B	Documented Gain
CO_2e Reduction (Operational + Embodied)	–	Qualitative Reduction Observed	Aligned with Decarbonisation Targets

behaviour and stable process control throughout all stages of pressure reduction. No surge or vibration trips occurred, confirming that the pre-implementation adequacy studies and FMEA risk-mitigation measures were effective. These findings are consistent with previous research showing that configuration adjustment and pressure re-balancing can safely increase throughput in mature facilities [18–20].

Collectively, the results demonstrate that pressure optimisation through mechanical rerouting and control refinement can restore production capacity while maintaining equipment reliability and process stability.

5.2 Comparative Performance and Benchmarking

When benchmarked against reported brownfield optimisation projects, which typically deliver 5–10 percent improvement in throughput [9, 10, 20], the LIMITLESS initiative achieved performance at the upper end of this range. The strong result reflects three critical enablers:

1. **A structured decision framework** integrating FMEA and AHP–TOPSIS to ensure that only high-impact, low-risk actions were prioritised.
2. **A phased execution plan** allowing validation at each suction-pressure stage before full implementation.
3. **Simulation-based verification** coupling process and network models to confirm system adequacy and mechanical integrity.

This disciplined workflow minimised operational uncertainty and allowed the team to validate technical outcomes within a controlled environment.

5.3 Economic and Sustainability Implications

The documented **value creation of IDR 419.52 billion (≈ USD 26 million)** underscores the commercial strength of optimisation-driven improvement compared with conventional hardware expansion. The result demonstrates that meaningful economic returns can be realised from existing assets when engineering, risk management, and system analysis are combined into a single workflow.

From a sustainability perspective, reduced recycle activity translated directly into lower fuel consumption and greenhouse-gas intensity. Avoiding the fabrication and installation of new compressor packages also prevented the embodied emissions associated with manufacturing and offshore mobilisation. The initiative therefore delivered both productivity and decarbonisation benefits, aligning with international frameworks such as the **World Bank Zero Routine Flaring 2030** and **Indonesia's Enhanced NDC (2022)** commitments.

5.4 Organizational Learning and Replicability

The cross-disciplinary execution of the LIMITLESS program strengthened coordination between process, operations, and reliability teams. Embedding structured tools such as FMEA and AHP–TOPSIS in the decision-making cycle improved transparency, shortened approval times, and enhanced accountability during design reviews.

This experience confirmed that technological measures alone do not ensure optimisation success. Equally important are organisational alignment, shared ownership, and iterative learning. The LIMITLESS workflow, **diagnose, analyse, simulate, implement, and monitor**, now serves as a replicable model for other brownfield facilities facing similar pressure-management challenges.

5.5 Broader Implications

Beyond the immediate production gains, this

work illustrates how **mature-asset revitalisation can function as a bridge between operational efficiency and energy-transition readiness**. By maximising existing infrastructure, operators can extend asset life, defer capital expenditure, and simultaneously lower emissions.

The LIMITLESS method provides a transferable framework that links reliability, cost efficiency, and sustainability. Its integration of diagnostic assessment, quantitative risk evaluation, and staged field execution demonstrates how traditional surface-facilities engineering can evolve into a strategic instrument for sustainable production recovery in the global upstream sector.

6. CONCLUSIONS

The study demonstrated that **strategic pressure optimisation**, supported by risk-based decision analysis and simulation validation, can effectively revitalise shut-in wells in mature offshore facilities without additional capital expenditure. The initiative confirmed that production losses were caused by surface constraints rather than reservoir depletion and that targeted reconfiguration within existing infrastructure could restore flow safely and efficiently.

Key conclusions are as follows:

1. **Surface pressure reduction as the primary enabler.** Lowering suction pressure from 140 psig to 90 psig successfully restored flow in wells previously constrained by high backpressure, validating that the production limitation was surface-driven rather than reservoir-related.
2. **Compressor configuration through rerouting.** Redirecting the discharge of GTC-624 into the suction of GTC-623 increased the effective compression ratio and enabled stable operation at reduced suction pressures. This modification achieved the required discharge pressure without additional compression hardware.
3. **Integrated risk-informed decision process.** The use of FMEA for risk identification, followed by AHP–TOPSIS for prioritisation, provided a transparent and data-driven framework for selecting the most effective and low-risk solution. This structure ensured that engineering interventions directly addressed verified operational bottlenecks.
4. **Validated production and economic performance.** The initiative achieved measurable throughput gains of 355 BOPD and 7.98 MMSCFD, generating a total value creation of IDR 419.52 billion (≈ USD 26 million). The results confirmed that optimisation-focused interventions can yield significant returns relative to cost.
5. **Contribution to sustainability objectives.** The reduction in recycle activity improved compressor energy efficiency and reduced fuel consumption, contributing to lower greenhouse-gas intensity. Avoiding new compressor fabrication also reduced embodied emissions, aligning the project with the World Bank *Zero Routine Flaring 2030* and Indonesia's *Enhanced NDC (2022)* targets.
5. **Replicability and broader relevance.** The LIMITLESS method, **Lowering Infrastructure Management and Integrated Throughput Enhancement for Sustainable Systems**, offers a scalable model applicable to other mature offshore and onshore assets. Its integration of diagnostics, risk assessment, and staged implementation demonstrates that production optimisation and sustainability can reinforce each other when guided by structured engineering discipline.

In conclusion, the LIMITLESS initiative confirms that operational excellence and sustainability are

not competing objectives but mutually reinforcing outcomes. By leveraging existing infrastructure through systematic, risk-informed engineering, mature fields can deliver additional value, reduce emissions, and extend their productive life, contributing to a more resilient and responsible energy future.

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TENTANG PENULIS



Nicky Leonard Nasution adalah seorang *Process & Surface Facilities Engineer* di PT Pertamina EP Cepu Zona 11, dengan pengalaman lebih dari sebelas tahun di bidang rekayasa fasilitas produksi minyak dan gas bumi. Ia memiliki keahlian dalam optimasi sistem proses, efisiensi energi, serta penerapan strategi keberlanjutan di fasilitas brownfield. Nicky aktif mengembangkan inovasi berbasis rekayasa sistem seperti metode LIMITLESS untuk revitalisasi sumur nonaktif melalui optimasi tekanan.

Selain berfokus pada peningkatan keandalan fasilitas, Nicky juga berperan dalam berbagai inisiatif pengembangan profesional, penelitian keberlanjutan, dan bimbingan akademik bagi mahasiswa teknik kimia. Ia memiliki ketertarikan khusus pada transisi energi, manajemen keberlanjutan, dan kepemimpinan strategis di sektor energi.



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Arief Rahman Dhuhri

A COMPREHENSIVE REVIEW OF LOW-CARBON HYDROGEN PRODUCTION FROM BIOMASS FEEDSTOCK POTENTIAL FOR INDONESIA WITH SWOT ANALYTICS

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ABSTRACT

Indonesia has abundant agricultural, plantation, and forestry residues—such as rice husk, rice straw, palm empty fruit bunches, wood pellets, and sugarcane bagasse—that can be used as feedstock for hydrogen production through biomass conversion. Various thermochemical, biochemical, and hybrid pathways have been explored; however, each still generates residual carbon dioxide that limits environmental benefits. To enhance sustainability, hydrogen production must be optimized by considering feedstock characteristics and techno-economic feasibility to support Indonesia's Net Zero Emission (NZE) 2060 target. This review evaluates biomass-based hydrogen production technologies in the Indonesian context through analysis of feedstock availability and characteristics, conversion methods, and techno-economic performance integrated within a SWOT framework. The approach systematically identifies opportunities, challenges, and strategic directions for developing a sustainable biomass-to-hydrogen system. The first stage maps key biomass residues in Indonesia, focusing on calorific value, ash content, and moisture level. The second stage qualitatively assesses different hydrogen production pathways, emphasizing their advantages, limitations, and readiness levels. Finally, the SWOT framework incorporates techno-economic insights to capture strategic strengths, weaknesses, opportunities, and threats. he insights derived from this study establish a robust scientific foundation for guiding research and technology development toward cost-effective, low-carbon hydrogen production—reinforcing Indonesia's long-term decarbonization and Net Zero Emission (NZE) 2060 commitment.

Keywords: *biomass conversion, low-carbon hydrogen, techno-economic assessment, SWOT analysis, sustainable energy*

1. INTRODUCTION

The global energy sector is undergoing a profound transformation in pursuit of carbon neutrality and climate change mitigation. Hydrogen has emerged as a pivotal energy carrier and chemical feedstock due to its high energy density, versatility, and potential to decarbonize hard-to-abate sectors such as heavy industry and transport (IEA, 2022). At present, hydrogen production is dominated by fossil fuel-based processes such as steam methane reforming and coal gasification, both of which are carbon-intensive and incompatible with long-term climate targets (Di Nardo et al., 2025). This has spurred growing interest in renewable and low-carbon hydrogen pathways, including water electrolysis powered by renewable energy and biomass conversion (Bai et al., 2025; Çelik et al., 2025).

Biomass is widely regarded as a carbon-neutral feedstock, as the CO_2 released during conversion is largely offset by CO_2 absorbed during growth. In addition, biomass residues from agriculture, forestry, and agro-industrial processes provide a sustainable and abundant supply for hydrogen production. Indonesia is endowed with considerable biomass potential, derived from resources such as rice husk, rice straw, palm empty fruit bunches, sugarcane bagasse, and wood residues (Aziz et al., 2021). Many of these residues remain underutilized or are disposed of through inefficient practices such as open burning, leading to environmental degradation. Their conversion into hydrogen could simultaneously mitigate waste challenges and support Indonesia's commitment to achieve Net Zero Emission (NZE) by 2060.

Several technological pathways are available for producing hydrogen from biomass. Thermochemical processes—such as combustion, pyrolysis, and gasification—are relatively mature, offering higher efficiencies and scalability for industrial deployment (Li et al., 2025; Pan et al., 2025). Biochemical processes—such as anaerobic digestion and fermentation—are environmentally benign but often constrained by low yields and slow kinetics (Aziz et al., 2021). Hybrid or emerging technologies, including supercritical water gasification, chemical looping, and co-pyrolysis with plastics, are increasingly studied for their potential to enhance hydrogen yield and reduce carbon emissions (Gao et al., 2023; Pan et al., 2025). Each pathway, however, presents distinct trade-offs in terms of efficiency, technological readiness, scalability, and cost.

Techno-economic assessments (TEA) have been widely applied to hydrogen production technologies to evaluate their economic and environmental competitiveness. Biomass-based hydrogen systems often face challenges related to feedstock logistics, conversion efficiency, and capital intensity, with reported levelized costs of hydrogen (LCOH) varying considerably depending on feedstock type, process configuration, and regional policy frameworks (Çelik et al., 2025; Bai et al., 2025). In Indonesia, additional constraints arise from the dispersed distribution of biomass resources, limited infrastructure, and competition with other bioenergy and pellet industries. In this context, a systematic evaluation that integrates techno-economic considerations within a SWOT framework is essential. This integrated approach enables the identification of suitable feedstock and conversion technologies while simultaneously capturing economic feasibility, strategic opportunities, and implementation barriers. Accordingly, this review provides a comprehensive assessment of biomass-based hydrogen production pathways through a techno-economically informed SWOT analysis, aiming to support research, industrial deployment, and policy formulation for Indonesia's transition toward low-carbon hydrogen and its NZE 2060 target.

2. LITERATURE REVIEW

2.1 Biomass Potential in Indonesia

Indonesia possesses vast biomass resources derived from agricultural, plantation, and forestry residues. According to Primadanty (2023), the total national potential of biomass energy reaches approximately 146.7 million tons per year, positioning biomass as the second-largest primary energy source after petroleum. The estimated **technical potential for power generation** from biomass is around **24.46 GW**, equivalent to about **150–170 million tons of oil equivalent (MTOE)** of annual energy supply (Outlook Energi Indonesia 2023–2033, 2023). Major contributions arise from agricultural by-products such as **rice husk, rice straw, palm empty fruit bunches (EFB), sugarcane bagasse, coconut shells, and wood residues**, which collectively dominate over 85% of Indonesia's total biomass potential (THS–Peran Bioenergi, 2023).

According to the Directorate General of New and Renewable Energy and Energy Conservation (Ditjen EBTKE, 2023), the **spatial distribution of biomass potential** is highly concentrated in **Sumatra (≈33%)**, **Kalimantan (≈26%)**, and **Sulawesi (≈12%)**, reflecting the geographic clustering of oil palm plantations, forestry industries, and rice production zones (Fig. 1). Java contributes mainly from agricultural residues—particularly rice husk and sugarcane bagasse—while eastern Indonesia (Maluku and Papua) remains relatively underutilized due to limited infrastructure.

In terms of fuel quality, Indonesian biomass feedstocks display diverse physicochemical characteristics. Rice husk and rice straw have calorific values of 13–15 MJ/kg, ash content up to 15–20%, and moisture levels around 10–15%, which influence gasifier design and tar management strategies (Dafiqurrohman et al., 2022). Palm residues—including EFB and fronds—typically show higher moisture (>50%) but also higher energy potential (17–18 MJ/kg) and availability year-round. Sugarcane bagasse provides a steady and concentrated feedstock around sugar mills, with moderate moisture (40–45%) and calorific value near 18 MJ/kg, making it suitable for integrated thermochemical hydrogen production. Wood pellets and sawmill residues

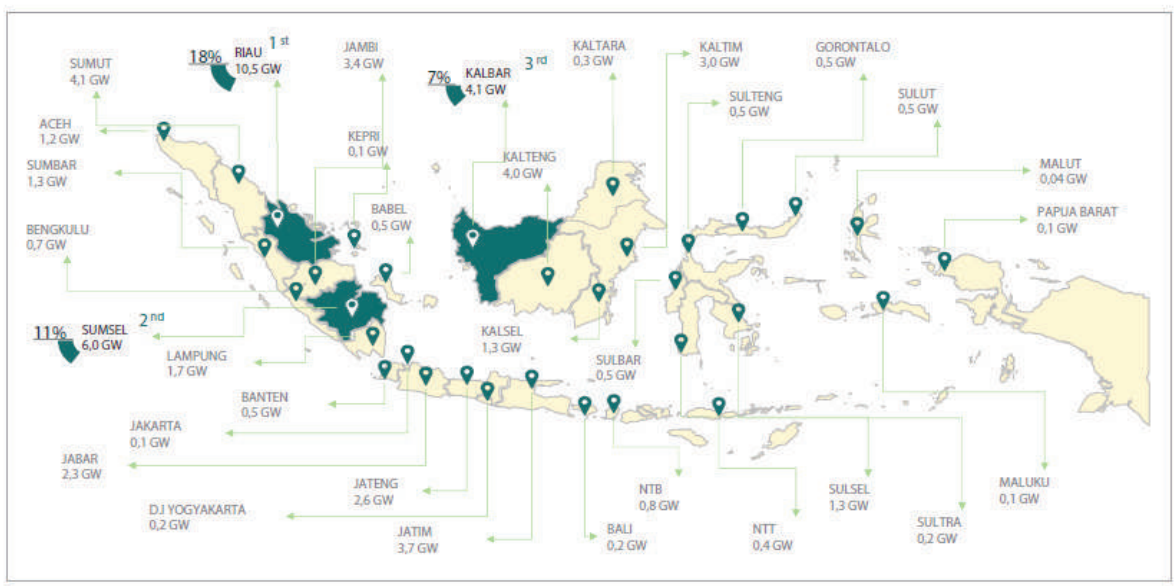


Figure 1. *Distribution Map of Indonesia's Bioenergy Potential*
Source: Ditjen EBTKE, 2023; Outlook Energi Indonesia 2023–2033

exhibit the highest energy density (18–20 MJ/kg) and the lowest ash content (<2%), supporting their use in stable gasification or co-firing systems.

Despite the abundance of biomass, several systemic challenges hinder large-scale utilization. Transportation and collection infrastructure remain underdeveloped, particularly in plantation areas of Sumatra and Kalimantan, where feedstock is spatially dispersed (IESR, 2024). Seasonal fluctuations in agricultural residue availability and competition with existing uses—such as pellet export, composting, or direct combustion—further constrain sustainable supply chains. Consequently, developing biomass-to-hydrogen systems in Indonesia requires not only matching the right feedstock–technology combination but also addressing logistics, preprocessing, and aggregation strategies to achieve economic feasibility.

2.2 Biomass-to-Hydrogen Conversion Technologies

Biomass can be converted into hydrogen through thermochemical, biochemical, or hybrid processes. Aziz et al. (2021) highlight that thermochemical routes—particularly gasification, pyrolysis, and steam reforming—demonstrate higher hydrogen yields and technological maturity compared to biological methods. Gasification is considered the most promising for large-scale applications, with hydrogen yields typically between 80–130 g/kg of dry biomass, depending on temperature and gasifying agent (e.g., steam, air, or oxygen). In contrast, biochemical processes such as dark fermentation or photo-fermentation achieve lower hydrogen yields (<30 g/kg) and slower kinetics, limiting their commercial viability. Recent studies also explore hybrid technologies, including supercritical water gasification and chemical looping gasification, which improve carbon conversion and reduce CO_2 emissions (Pan et al., 2025). In the Indonesian context, rice husk gasification has received substantial research attention (e.g., Di Nardo et al., 2025; "Gasification of Rice Wastes toward Green and Sustainable Energy Production," 2022). These studies report high hydrogen yields with relatively low tar formation when operated at 700–900 °C, making it feasible for decentralized applications in rural areas with abundant agricultural residues.

To provide a clearer comparative perspective, the main hydrogen production pathways are summarized in Table 1. Each pathway represents a distinct conversion mechanism with specific process conditions, hydrogen yields, and readiness levels. Thermochemical routes—including gasification, pyrolysis, and steam reforming—are generally more mature and efficient; while emerging and hybrid technologies such as chemical looping and supercritical water gasification (SCWG) offer improved carbon efficiency and integration potential for wet or complex feedstocks. The table outlines the operating principles, advantages, and limitations of these pathways as reported in the reviewed literature, serving as a foundation for the subsequent SWOT-based assessment of their applicability to Indonesia's biomass resources.

The comparison presented in Table 1 demonstrates that thermochemical routes—particularly **gasification and steam reforming**—are the most technologically mature and widely validated for large-scale hydrogen production. These processes align closely with Indonesia's dominant feedstocks, such as **sugarcane bagasse, palm residues, rice husk, and wood waste**, which exhibit favorable energy densities and conversion efficiencies under gasification conditions. **Pyrolysis** offers flexibility for decentralized or small-scale systems but islimited by the complex composition of bio-oil and lower hydrogen yield. Among emerging options, **supercritical water gasification (SCWG)** provides a promising pathway for wet feedstocks like **EFB** or **palm oil mill effluent**, while **chemical**

Table 1. *Hydrogen Production Pathway*

PATHWAY	DESCRIPTION	ADVANTAGES	LIMITATIONS	REFERENCES
Gasification (Steam/ Oxygen/ Air)	Thermal conversion of solid biomass into synthesis gas (mainly H_2, CO, CO_2, CH_4) at 700–1100 °C, often followed by water–gas shift and hydrogen purification (PSA or membrane).	• Technologically mature and scalable. • High hydrogen yield (typically 80–130 g H_2/ kg biomass). • Applicable to a wide range of feedstocks. • Steam gasification enhances H_2/CO ratio.	• Tar formation and ash/ slagging issues, particularly for silica-rich residues such as rice husk. • Requires extensive gas cleaning and reforming stages. • High CAPEX/OPEX for small-scale units.	Aziz et al. (2021); Dafiqurrohman et al. (2022)
Pyrolysis (Fast/ Slows/ Catalytic)	Thermal decomposition of biomass in the absence of oxygen (400–650 °C) to produce bio-oil, bio-char, and gases. Hydrogen can be generated via catalytic or steam reforming of the bio-oil fraction.	• Produces multiple value-added products (bio-oil, biochar, H_2). • Flexibility in operating conditions and product selectivity. • Suitable for small-scale distributed systems.	• Complex composition of bio-oil requires pretreatment and catalytic upgrading. • Catalyst deactivation (coking) and system complexity increase costs. • Lower overall H_2 yield compared with direct gasification.	Aziz et al. (2021)
Steam Reforming/ Partial Oxidation of Bio-oil or Biogas	Catalytic reaction of carbonaceous gases or liquids with steam or limited oxygen to form syngas (CO + H_2), followed by WGS for hydrogen enrichment.	• High conversion efficiency and TRL (TRL > 8). • Reduces external heat demand. • Compatible with integrated biorefineries.	• Steam requirement increases energy consumption. • Catalyst sensitivity to impurities and carbon deposition. • Requires high-purity feedstock or extensive pre-cleaning.	Aziz et al. (2021); Luo et al. (2025).
Hybrid Thermo-Biological Systems	Integrates thermochemical steps with biological processes for sequential hydrogen generation.	• Enables utilization of both solid and liquid fractions of biomass. • Expands potential feedstock range.	• Low overall kinetics and complex process integration. • Mainly conceptual or lab-scale research.	Aziz et al. (2021).
Chemical Looping Gasification (CLG)/ Reforming (CLR)	Utilizes a solid oxygen carrier (e.g., Fe, Ni, Mn) in two interconnected reactors for fuel oxidation and air regeneration, producing a CO_2-concentrated stream and hydrogen-rich syngas.	• Inherent CO_2 separation enables low-carbon or negative-carbon operation. • Potentially higher overall efficiency than conventional gasification. • Suitable for integration with power generation.	• Limited to pilot scale; carrier material degradation (attrition, sintering). • Complex reactor design and heat management. • High CAPEX compared with fixed-bed systems.	Aziz et al. (2021); Pan et al. (2025).

Supercritical Water Gasification (SCWG)	Converts wet biomass (> 50% moisture) into H_2-rich gas using supercritical water (T > 374 °C, P > 22 MPa). Reactions include hydrolysis, reforming, and WGS.	• Eliminates drying step for wet feedstocks (EFB, POME, algae). • High conversion efficiency with low tar formation. • Suitable for liquid or slurry biomass streams.	• High pressure and temperature demand robust reactor materials (corrosion). • High CAPEX/OPEX and maintenance. • Limited large-scale demonstration data.	Aziz et al. (2021); Luo et al. (2025).
Co-Gasification/ Co-Pyrolysis (Biomass + Plastic or Coal Blends)	Co-processing biomass with coal or plastics to enhance H_2 yield and syngas quality through synergistic reactions.	• Increases gas quality and conversion efficiency. • Allows simultaneous treatment of plastic or coal waste. • Can reduce tar formation depending on blend ratio.	• Feedstock heterogeneity introduces contaminants (Cl, metals). • Higher gas-cleaning requirements. • Sustainability concerns if fossil co-feeds are used.	Aziz et al. (2021)

looping gasification (CLG) introduces an intrinsic carbon-capture capability that supports low-carbon or even negative-emission operation. However, both SCWG and CLG remain at pilot-scale development and face high capital and material challenges. Overall, these findings indicate that thermochemical gasification and its advanced variants hold the greatest relevance for Indonesia's biomass landscape, forming the analytical basis for the subsequent **SWOT assessment** of feedstock–technology feasibility in achieving low-carbon hydrogen production.

2.3 Techno-Economic and Environmental Aspects

Techno-economic assessments (TEA) of biomass-based hydrogen systems aim to evaluate cost competitiveness relative to fossil-based hydrogen. Reported Levelized Cost of Hydrogen (LCOH) values vary between US$3–6/kg H_2 depending on feedstock type, conversion technology, and plant scale (Çelik et al., 2025; Bai et al., 2025). In Indonesia, costs tend to be on the higher side due to limited supply-chain infrastructure, high feedstock moisture, and transportation distances from plantation to processing sites.

From an environmental standpoint, biomass hydrogen is categorized as "green" or "renewable" only when produced from residues and coupled with carbon capture and storage (CCS) or carbon recycling systems. Otherwise, CO_2 emissions from the conversion process remain significant. Aziz et al. (2021) emphasize that thermochemical conversion of biomass still generates substantial CO_2, but integration with chemical looping or CO_2 capture can reduce net emissions to near zero. The Comparative Review of Carbon Emissions from Hydrogen Production Technologies (2022) identifies that biomass-based hydrogen emits 3–6 kg CO_2/kg H_2 without CCS, compared to >10 kg CO_2/kg H_2 from steam methane reforming. Implementing CCS could reduce biomass-based emissions by up to 90%. These findings highlight the importance of in-situ CCS integration in future biohydrogen projects.

2.4. SWOT as an Analytical Framework

SWOT analysis has been widely utilized in energy and technology assessment studies to complement quantitative evaluations such as techno-economic or life-cycle analyses. In the context of renewable energy, SWOT provides a structured and strategic framework to identify internal and external factors influencing

technology deployment—capturing not only technical performance but also policy, market, and infrastructural dynamics. Prior research has demonstrated that SWOT is particularly useful in early-stage or emerging technologies, where data limitations make purely numerical models insufficient for comprehensive evaluation (Lee et al., 2023; Al-Mashaqbeh et al., 2024). For hydrogen and bioenergy systems, SWOT facilitates the integration of technical indicators (e.g., conversion efficiency, cost, resource availability) with qualitative dimensions such as institutional readiness and investment potential (Çelik et al., 2025; IESR, 2024).

3. METHODOLOGY

This study adopts a systematic, multi-stage approach to evaluate biomass-based hydrogen production technologies in the Indonesian context. The methodological framework is designed to bridge quantitative and qualitative analysis, integrating feedstock assessment, literature screening, techno-economic evaluation, and SWOT analysis. This structure allows a comprehensive assessment of hydrogen production pathways by combining empirical data, contextual analysis, and strategic interpretation.

The first stage, data gathering, involves collecting information from academic databases—**Scopus, Web of Science, ScienceDirect, and SpringerLink**—covering publications from **2000 to 2025**. Search keywords included *"biomass gasification"*, *"biohydrogen production"*, *"biomass potential Indonesia"*, *"techno-economic analysis of hydrogen"*. Boolean logic was applied to refine search strings, e.g., ("biomass" OR "bioenergy") AND ("hydrogen production" OR "H_2 generation") AND ("Indonesia" OR "Southeast Asia"). Data cover feedstock availability, physical and chemical characteristics (such as calorific value, ash content, and moisture level), conversion efficiency, and indicative cost parameters across thermochemical, biochemical, and hybrid processes.

The second stage, document screening, focuses on identifying and selecting relevant studies that specifically address biomass utilization for hydrogen production in Indonesia or comparable regional contexts. Duplicates, documents with incomplete data, outdated statistics, or inconsistent methodologies are excluded to ensure reliability and analytical coherence. Abstract-level screening is followed by a full-text evaluation to assess methodological soundness, data completeness, and regional applicability. Only high-quality studies meeting these criteria are retained for synthesis and comparative analysis.

This process initially retrieved 4,218 records, from which 1,965 duplicates were removed. The remaining 2,253 studies underwent abstract-level screening to identify those specifically addressing biomass utilization for hydrogen production or low-carbon energy transition scenarios in Indonesia and comparable regional contexts. Full-text assessment was then performed on 512 shortlisted papers to evaluate methodological rigor, data completeness, and regional applicability. A total of 276 high-quality studies were retained and subsequently analyzed to extract feedstock characteristics, process efficiencies, conversion technologies, and indicative cost structures.

The third stage, SWOT assessment, integrates techno-economic considerations into strategic analysis. Strengths include feedstock potential, technological flexibility, and alignment with national decarbonization goals. Weaknesses represent internal aspects such as technological maturity, cost performance, and resource quality, while opportunities and threats capture external factors including policy environment, infrastructure readiness, and market potential.

This integrated framework combines quantitative techno-economic indicators and

qualitative contextual factors within the SWOT analysis. Through this combined methodological approach, the review not only consolidates existing scientific findings but also highlights their relevance to Indonesia's energy transition and Net Zero Emission (NZE) 2060 target, positioning biomass-based hydrogen as one of the strategic pillars in the nation's sustainable energy roadmap.

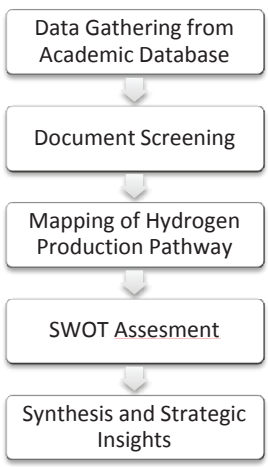


Figure 2. *Methodology Framework*

4. RESULT AND DISCUSSION

4.1 SWOT Analysis for Biomass-to-Hydrogen Pathways in Indonesia

Table 2 presents a synthesized SWOT matrix summarizing key internal and external factors influencing the feasibility of biomass-to-hydrogen systems in Indonesia. The analysis integrates findings from previous literature, techno-economic assessments, and national biomass data.

The SWOT analysis highlights both the strategic advantages and the operational barriers facing Indonesia's biomass-to-hydrogen development. The main strengths lie in the country's abundant biomass potential and existing industrial infrastructure that can support co-located conversion systems. Feedstocks such as sugarcane bagasse and palm empty fruit bunches (EFB) offer large, consistent volumes suitable for hydrogen production. Bagasse, concentrated around sugar mills, provides an efficient logistics network

Table 2*. SWOT Analysis of Biomass-to-Hydrogen Development in Indonesia*

CATEGORY	KEY FACTORS	IMPLICATIONS
Strengths (S)	• Abundant and diverse biomass feedstocks (bagasse, EFB, rice husk, wood residues) distributed across major islands. • Existing agro-industrial facilities (sugar mills, palm-oil mills, saw-mills) enable co-location of conversion units. • Technologically mature thermochemical pathways (gasification, steam reforming) with proven performance and scalability.	Provides a strong resource and infrastructure base for near-term deployment of hydrogen production using conventional gasification systems.
Weaknesses (W)	• High moisture and ash content in certain residues (EFB, rice husk) reduce conversion efficiency and increase preprocessing cost. • Logistics and feedstock aggregation remain challenging, particularly in dispersed plantation areas. • Limited large-scale operational data for advanced processes (SCWG, chemical looping).	Technical and logistical inefficiencies may raise the levelized cost of hydrogen (LCOH) and reduce system reliability.
Opportunities (O)	• Growing global and domestic demand for low-carbon hydrogen (IESR, 2025). • Availability of carbon-rich wet biomass enabling integration with carbon-capture or negative-emission technologies. • Potential industrial symbiosis with existing bioenergy or cogeneration plants.	Expanding energy-transition initiatives and decarbonization targets create strategic momentum for investment in biomass-based hydrogen.
Threats (T)	• High initial CAPEX for advanced technologies (SCWG, chemical looping). • Competition with existing biomass uses (pellets, power generation). • Uncertainty in feedstock supply chains and market readiness.	Financial risk and technological immaturity may delay commercialization without targeted demonstration and cost-reduction strategies.

Source: Synthesized from Aziz et al. (2021); Dafiqurrohman et al. (2022); Luo et al. (2025); Primadanty (2023); IESR (2024, 2025); DEN (2023).

and relatively favorable fuel quality—low ash, moderate moisture, and high calorific value—making it the most promising candidate for steam or fluidized-bed gasification (Aziz et al., 2021).

However, notable weaknesses include high preprocessing costs for moist or silica-rich feedstocks, such as EFB and rice husk, and a lack of standardized feedstock-collection systems across regions. These technical constraints elevate the LCOH, especially for small-scale systems. Meanwhile, emerging technologies such as supercritical water gasification (SCWG) and chemical looping gasification (CLG) present major opportunities to convert wet biomass efficiently and reduce CO_2 emissions through inherent carbon separation (Luo et al., 2025; Pan et al., 2025). Yet, their current threats lie in high capital intensity, material degradation under extreme operating conditions, and limited demonstration at commercial scale.

Overall, the SWOT framework underscores that thermochemical gasification and its advanced derivatives represent the most immediately viable routes for Indonesia. These findings provide the analytical foundation for selecting suitable feedstock–technology pairs and evaluating their techno-economic feasibility.

4.2 Techno-Economic Comparison of Promising Feedstock–Technology Combinations

To translate SWOT findings into actionable insights, Table 5 compares three promising feedstock–technology combinations based on literature-derived performance indicators. Data were synthesized from the reviewed references and representative techno-economic analyses of biomass-to-hydrogen systems.

Table 3. *Comparative Techno-Economic Characteristics of Selected Biomass-to-Hydrogen Pathways*

FEEDSTOCK–TECHNOLOGY PAIR	KEY PROCESS FEATURES	CONVERSION EFFICIENCY	INDICATIVE LCOH (USD / KG H_2)	TRL	KEY CONSIDERATIONS	REFERENCES
Sugarcane Bagasse + Steam Gasification → WGS → PSA	Thermochemical conversion of dry bagasse using steam; suitable for centralized sugar-mill integration.	55–65 % (overall energy efficiency)	2.5 – 3.0	TRL 8–9	Mature process, low logistics cost; limited by seasonal bagasse supply.	Aziz et al. (2021); Luo et al. (2025).
Wood Residues + Air/Oxygen Gasification + Syngas Cleaning	Fixed or fluidized-bed gasifier for low-ash woody feedstock; integration with WGS for H_2 production.	50–60 %	2.8 – 3.5	TRL 7–8	Stable operation and high syngas quality; dispersed feedstock availability.	Dafiqurrohman et al. (2022); THS–BPPT (2023).
Palm EFB (Wet Feedstock) + Supercritical Water Gasification (SCWG)	Direct gasification of wet biomass under supercritical conditions (> 22 MPa, > 374 °C).	60–70 % (feedstock-to-gas basis)	4.0 – 6.0	TRL 5–6	Eliminates drying stage; high CAPEX and material cost; corrosion issues.	Aziz et al. (2021); Pan et al. (2025); IESR (2024).

4.3 Discussion of Techno-Economic Results

The comparative results reinforce that bagasse-based steam gasification is currently the most technically and economically feasible pathway for Indonesia's near-term hydrogen production. Its centralized feedstock supply at sugar mills offers logistical efficiency and process stability, yielding a competitive LCOH of 2.5–3.0 USD/kg H_2, aligning with reported global benchmarks (Aziz et al., 2021). Wood-residue gasification demonstrates similar efficiencies but is constrained by dispersed resource distribution and competition with pellet export markets.

Conversely, EFB-based SCWG presents a strong long-term prospect for low-carbon hydrogen due to its ability to process wet biomass without drying, achieving higher conversion efficiencies. Nevertheless, high system pressure and material corrosion significantly increase CAPEX, pushing LCOH above 4 USD/kg H_2 at current technology maturity (Pan et al., 2025). As material research and process intensification progress, SCWG could evolve into a preferred pathway for palm-oil-industry residues.

From a strategic viewpoint, combining the SWOT and techno-economic results reveals a clear development hierarchy:

- Short-term (now–2030): Deploy conventional gasification for bagasse and wood residues at existing agro-industrial sites.
- Medium-term (2030–2040): Pilot and scale up SCWG for wet biomass such as EFB and POME.
- Long-term (beyond 2040): Integrate chemical looping or hybrid systems for carbon-negative hydrogen aligned with Indonesia's Net Zero Emission 2060 target.

These staged recommendations align with current R&D priorities outlined by BPPT and IESR (2024) and provide a strategic roadmap linking resource potential, technological readiness, and decarbonization objectives.

5. CONCLUSION

The combined SWOT and techno-economic analyses provide a holistic perspective on Indonesia's biomass-to-hydrogen landscape. While the country's abundant feedstock base and mature thermochemical know-how present substantial opportunities, success will depend on reducing logistical inefficiencies and advancing demonstration-scale projects for emerging technologies.

Among the various pathways reviewed, thermochemical conversion—particularly steam gasification of sugarcane bagasse—emerges as the most promising biomass–technology pairing for Indonesia. Bagasse provides stable and concentrated feedstock availability, low ash content, and well-established collection systems within sugar-milling industries. When integrated with water–gas shift (WGS) and pressure swing adsorption (PSA) units, bagasse gasification can achieve hydrogen yields of 80–120 g H_2/kg feedstock and competitive levelized costs of 2.5–3.0 USD/kg H_2, aligning with international techno-economic benchmarks. Wood residues represent a secondary but viable alternative, suitable for decentralized applications using air- or oxygen-blown gasification systems. In contrast, emerging hybrid technologies—such as supercritical water gasification (SCWG) and chemical looping gasification (CLG)—demonstrate potential for processing wet or low-grade biomass with reduced CO_2 emissions. However, their commercialization is still limited by high capital costs, material degradation under extreme conditions, and lack of large-scale validation.

In conclusion, bagasse-based steam gasification stands out as the most immediate and technically feasible thermochemical route for low-carbon hydrogen production in Indonesia. Meanwhile, SCWG and CLG represent the long-term innovation frontiers that can enhance carbon efficiency and support the nation's Net Zero Emission (NZE) 2060 vision through advanced negative-emission hydrogen systems.

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HYBRID SOLAR-DIESEL SYSTEMS FOR SUSTAINABLE ENERGY **RESILIENCE IN INDONESIAN CONSTRUCTION PROJECTS**

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ABSTRACT

Construction projects in Indonesia predominantly depend on diesel engine generators (gensets) for temporary power during execution, leading to substantial fuel expenses, greenhouse gas emissions, and operational inefficiencies. This study investigates a hybrid solar-diesel system that integrates portable photovoltaic (PV) modules and battery storage to offset diesel usage during construction phases. Leveraging Indonesia's average solar irradiation of 4.5–5.5 kWh/m^2/day and aligning with the National Energy Policy (RUEN) target of 23% renewable share by 2025 [12][14], the proposed system achieves up to 50% fuel savings and equivalent CO_2 reduction. A 100 kVA generator case study quantifies operational savings, compares economic metrics such as LCOE, and provides phased implementation guidance. Benchmarking against regional studies [1][3][6][11] confirms that hybrid solar-diesel systems can deliver 40–50% reductions in fuel consumption, improve project sustainability, and align with corporate Environmental, Social, and Governance (ESG) goals.

Keywords: Construction power supply, diesel generator reduction, solar photovoltaic (PV), hybrid energy systems, battery storage, renewable energy, Indonesia, sustainable construction

1. INTRODUCTION

Diesel engine generators remain the primary power source during the construction and commissioning phases of oil and gas facilities in Indonesia. Their reliability and portability make them a preferred choice for temporary power supply, ensuring seamless operations in remote and off-grid locations. However, the extensive use of gensets contributes to escalating fuel costs, elevated noise levels, and substantial CO_2 emissions. The environmental impact and operational expenses associated with diesel generators have become a growing concern for construction project stakeholders.

Indonesia's abundant solar energy potential, exceeding 4.8 kWh/m^2/day across much of the country, presents an opportunity to offset diesel consumption through hybrid solar-diesel configurations. These systems combine portable solar photovoltaic (PV) modules and battery storage with traditional diesel gensets, creating a technically feasible and economically viable

alternative for meeting temporary construction power needs. While previous studies have explored hybrid systems in remote island settings [1][3][6], limited research has addressed their application in transient, high-demand construction operations. This study addresses this gap by developing a practical framework for integrating PV-battery systems into construction site power setups. It includes a quantification of performance metrics and aligns implementation strategies with the phased execution of Engineering, Procurement, and Construction (EPC) projects.

Diesel engine generators, despite their widespread use in construction, impose high operational costs, generate significant noise pollution, and contribute to substantial greenhouse gas emissions. The volatility of fuel prices and the emissions from diesel combustion, including CO_2, NOx, and particulate matter, further impact the sustainability of construction activities. With advancements in solar panel efficiency and reductions in lithium battery costs, hybrid solar-diesel systems are now able to compete economically with conventional gensets. This offers a cleaner and potentially more cost-effective solution for construction sites, particularly during daylight hours when solar resources can be maximized.

At construction sites, diesel gensets are favored for their ability to provide portable, off-grid power for a wide range of activities. However, fuel consumption during the construction phase is largely driven by the operation of these generator sets, which consistently outpace the fuel usage of cranes, vehicles, and site lighting. This heavy reliance results in increased operational and maintenance expenditures and positions gensets as a major source of carbon dioxide emissions, impacting the overall environmental footprint of the project.

Not all generators operate continuously; certain zones within construction sites require round-the-clock or nighttime power to meet specific energy demands. This pattern of utilization highlights the importance of assessing genset deployment and operating hours to identify opportunities for optimization. A thorough understanding of genset usage patterns and their implications for both costs and emissions is essential for developing effective strategies to enhance sustainability and cost efficiency. By analyzing the distribution and demand for temporary power, project teams can pinpoint opportunities to optimize energy sources, thereby reducing the environmental and financial burdens associated with diesel generator use.

2. CASE STUDY

Typical power ratings for construction gensets range from 30–500 kVA, supplying electricity for lighting, welding machines, pumps, and site offices. A 100 kVA genset consumes approximately 22–25 liters/hour at 75% load. If operated 10 hours/day for 250 days/year, this equates to around 55,000 liters of diesel annually. This consumption produces roughly 60 tonnes of CO_2 emissions per year for a single unit, alongside noise levels between 75–90 dB and regular maintenance requirements.

The chart below provides data collected from an oil and gas construction project in 2023. This information details the deployment and utilization patterns of gensets across various activity categories. The data highlights the number of gensets assigned to infrastructure support, commissioning, construction, and preservation tasks, as well as the variation in diesel fuel consumption among individual units. The findings emphasize operational variability, with some gensets operating continuously and consuming significantly more fuel than others. This operational profile is crucial for understanding the distribution of diesel usage and associated emissions within the project.

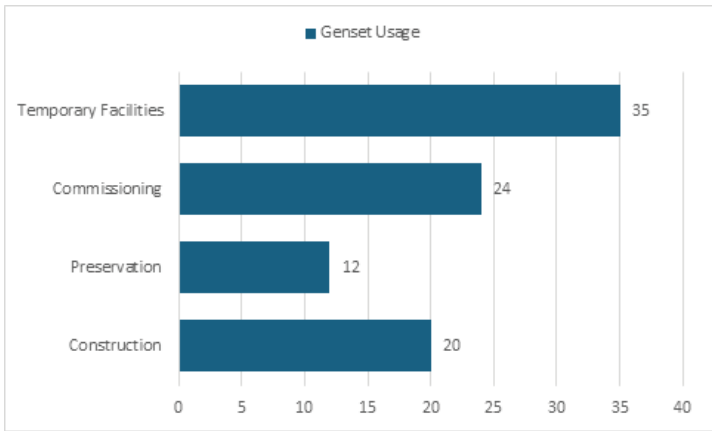


Figure 1. *Diesel generator data usage in 2023 for an oil and gas project.*

The monthly analysis of diesel consumption indicates that the average generator set utilizes approximately 768 liters per month, whereas the highest-consuming unit records usage of about 3,510 liters per month—representing an increase of roughly 4.5 times. This disparity underscores operational variability and extended run times in specific areas.

Each 100 kVA generator set emits approximately 60 tonnes of CO_2 annually, based on standard load assumptions and operating hours. With 91 units in operation, total estimated annual emissions reach 5,460 tonnes of CO_2. The accompanying pie chart displays the distribution of CO_2 emissions by activity category according to genset usage.

Solar PV systems for construction sites can consist of solar panels, charge controllers, inverters, battery storage, and a hybrid controller to manage load sharing between diesel and solar sources. In Indonesia, average daily solar irradiation is between 4.5–5.5 kWh/m^2/day, allowing for high PV output even with mobile arrays. A hybrid system can power site offices, lighting, and smaller tools during the day, with diesel used only at night or during low-sunlight conditions.

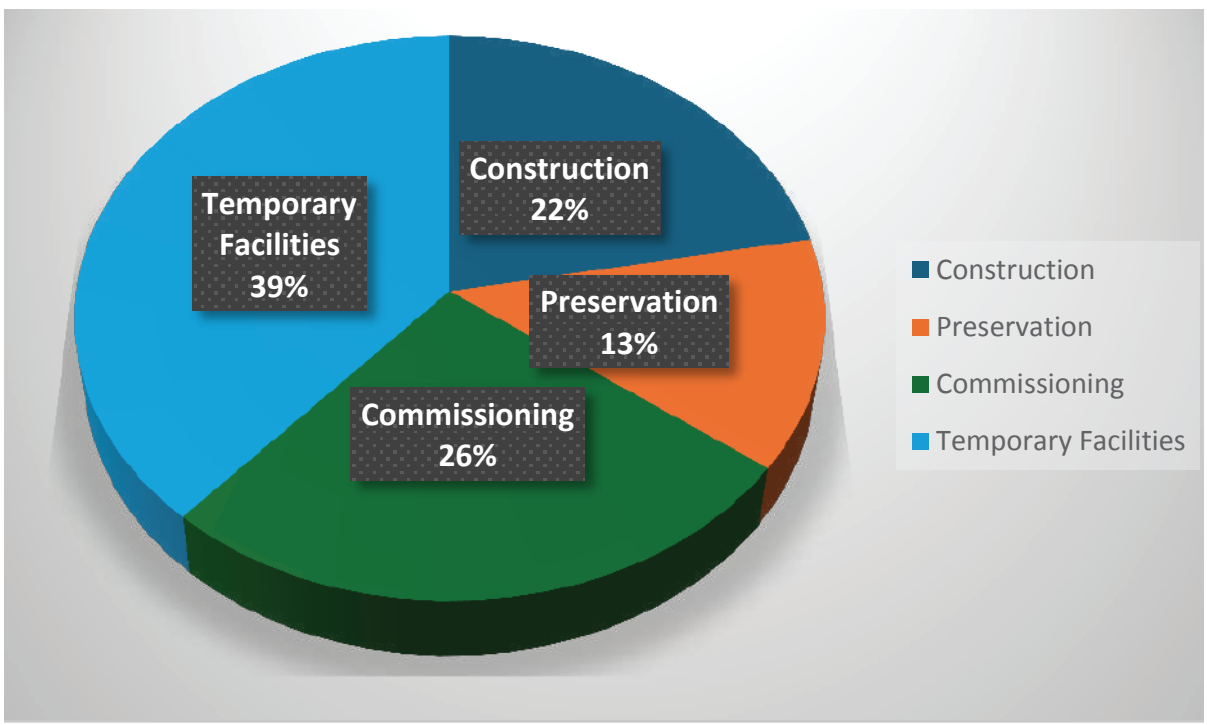


Figure 2: *Estimated CO2 emissions for 91 Diesel Genset in 2023*

This case study will establish the calculation framework for the implementation of Solar PV Systems, as detailed below.

The required photovoltaic area is calculated based on a solar panel efficiency of approximately 20%.

$$PV\ Area = \frac{EL}{G_{AV} \times \eta PV} \quad (1)$$

Based on the required PV area calculated in equation (1), the electrical power generated by the solar panel is as follows:

$$PV_{watt\ peak} = PV\ area \times PSI \times \eta PV \quad (2)$$

The quantity of photovoltaic (PV) panels required can be determined using the following equation:

$$Number\ of\ Panels = \frac{PV_{watt\ peak}}{Panel\ Rating}$$

Subsequently, the battery backup will be determined according to the assessed power demand.

$$Battery\ Capacity = \frac{EL}{Depth\ of\ Discharge\ (DoD)} \quad (4)$$

The battery capacity has been adjusted based on an efficiency rate of 85%.

$$Battery\ Capacity = \frac{Required\ Battery\ Capacity}{Efficiency} \quad (5)$$

The required number of batteries will be determined using the following equation:

$$Number\ of\ batteries = \frac{Required\ Battery\ Capacity}{Capacity\ per\ Battery} \quad (6)$$

Where:

EL : Energy Consumption, kWh/day
GAV : Daily Solar Irradiation, kWh/m²/day
ηPV : PV Panel Efficiency, %
PSI : Peak Solar Irradiance, W/m² (standard)

2. METHODOLOGY OF IMPLEMENTATION

Based on the data presented in the above case study, the following tables summarize the input data and calculation results.

Table 1. *Input Parameters & Assumptions*

PARAMETER	VALUE	UNITS / NOTES
Daily Energy Consumption (EL)	320	kWh/day
Daily Solar Irradiation (GAV)	5.0	kWh/m²/day
PV Panel Efficiency (ηPV)	20%	fraction used in calc
Peak Solar Irradiance (PSI)	1,000	W/m² (standard)
Panel Rating	350	Wp per module
Depth of Discharge (DoD)	90%	battery DoD assumption
Battery Round-Trip Efficiency	85%	overall efficiency

Table 2. *Step-by-Step Calculations*

STEP	FORMULA	RESULT
PV Area	Area = EL / (GAV × ηPV)	320 m²
PV Peak Power	PV_wp = Area × PSI × ηPV	64.0 kWp
No. of Panels	Panels = PV_wp / Panel Rating	183 panels
Battery (req.)	EL / DoD	355.56 kWh
Battery (adjusted)	Required / Efficiency	418.30 kWh
No. of Batteries	Adjusted / 24 kWh	18 units

The model calculation assumes 10 hours/day operation with 75% average load.

The hybrid energy system is designed so that the photovoltaic (PV) installation will offset approximately 50% of the site's total load demand, with the remaining 50% supplied by a diesel generator set. This load-sharing configuration is expected to yield significant reductions in fuel consumption and CO2 emissions. The tables below provide a detailed comparison, illustrating the anticipated decreases in diesel usage and environmental impact when the PV system is integrated alongside the conventional generator.

The Levelized Cost of Energy (LCOE) and simple payback period were analyzed based on assumptions adapted from [4][8][11]. The PV CAPEX was estimated at USD 1,000/kWp and diesel fuel cost at IDR 15,000/L.

A parametric analysis was conducted for PV efficiency (18–22%) and diesel price variation (±20%), following [2][9]. A 10% improvement in PV efficiency or a 15% fuel price rise can shorten payback to 1.6 years.

Table 7 presents a comparison between the findings of this study and those reported by other

Table 3: *Annual Fuel Consumption*

Scenario	Fuel Consumption (L/year)	Fuel Savings	% Reduction
Diesel Only	838,800	—	—
Hybrid Solar (50% offset)	419,400	419,400 L/year	50%

Table 4: *Annual Fuel Cost*

Scenario	Fuel Cost (IDR/year)	Equivalent (USD)	Savings (IDR)	Savings (USD)
Diesel Only	12,582,000,000	825,700	—	—
Hybrid Solar	6,291,000,000	412,850	6,291,000,000	412,850

Table 5: *Economic Evaluation (LCOE and Payback)*

Scenario	LCOE (USD/kWh)	Annual Cost (USD)	Payback Period
Diesel Only	0.82	825,700	—
Hybrid Solar	0.43	412,850	~2 years

Table 6: *Annual CO_2 Emissions*

Scenario	CO_2 Emissions (tonnes/year)	CO_2 Reduction	% Reduction
Diesel Only	5,460	—	—
Hybrid Solar	2,730	2,730 tonnes/year	50%

Table 7: *Benchmarking Comparison*

Reference	Location	PV Share (%)	Diesel Reduction (%)	CO_2 Reduction (t/year)
[1] Zuhri et al. 2025	Bunaken Island	45	52	2,400
[3] IJIREEICE 2019	Karimun Jawa	50	43	2,200
[6] Suhendra et al. 2023	East Java	40	47	1,800
This Study (2025)	**Onshore Project**	**50**	**50**	**2,730**

published hybrid systems.

This benchmarking confirms that the system achieves comparable or higher diesel displacement and CO_2 reduction than previous studies.

For 91 gensets across project sites, annual CO_2 emissions reach approximately 5,460 tonnes under diesel-only operations. The hybrid configuration reduces this by half, cutting emissions by 2,730 tonnes. The CO_2 abatement cost equates to ~USD 150/tonne, well below Indonesia's shadow carbon price of USD 220/t [IEEFA 2019].

Hybrid Solar Systems in Construction: Operational Savings and Environmental Impact

The implementation of hybrid solar systems during the construction and commissioning phases offers considerable advantages for project operations. By integrating solar photovoltaic (PV) technology with conventional diesel generators, projects can achieve notable operational cost savings and environmental improvements.

Operational Cost Reduction

Analysis of diesel fuel consumption and generator (genset) deployment in the case study demonstrates that transitioning to a hybrid solar-diesel configuration can significantly decrease dependence on diesel generators. This reduction leads to lower fuel expenditures and less frequent maintenance requirements, thereby improving overall project efficiency.

Environmental Benefits

Adopting a hybrid approach also allows for quantifiable reductions in carbon dioxide (CO_2) emissions, supporting sustainability objectives for large-scale construction projects. These reductions not only enhance the environmental profile of the project but also contribute to broader corporate sustainability targets.

Operational Considerations

Despite these benefits, certain operational limitations must be acknowledged. When energy demands extend beyond 10 hours per day, supplementary diesel fuel may be required as a backup, especially during periods of limited solar availability. This highlights the importance of meticulous load management and strategic planning to ensure reliable integration of solar PV systems into construction site energy solutions.

Implementation Guidance for Hybrid Solar Systems in the EPC Stage

To effectively implement this hybrid solar proposal during the Engineering, Procurement, and Construction (EPC) phase of a project, a phased approach is recommended. This ensures practical deployment, maximized benefits, and manageable transition for all project stakeholders.

1. Phase 1 – Pilot Deployment

Begin by deploying mobile 30–50 kWp photovoltaic (PV) units paired with 100 kWh battery systems on one or two large construction sites. This pilot phase allows the project team to assess operational performance, adapt to site-specific needs, and gather data on fuel savings and emission reductions.

2. Phase 2 – Scale-Up

Upon successful demonstration, expand the deployment to all construction sites with project durations exceeding 12 months. This phase aims to extend the benefits of operational savings and environmental impact across a broader portfolio of sites, ensuring consistency and scalability.

3. Phase 3 – Centralized Integration

For long-term optimization, centralize procurement and leasing of solar kits to serve multiple projects. This integration streamlines logistics, reduces costs through bulk purchasing or leasing arrangements, and ensures standardized implementation across all projects.

4. Mitigation of Implementation Barriers

- **Initial investment cost**: Address capital expenditures by exploring equipment leasing options or forming partnerships with EPC contractors.
- **Space requirements**: Utilize containerized or mobile foldable PV arrays to accommodate space constraints on active construction sites.
- **Load peaks**: Ensure hybrid system design supports automatic switchover between diesel, solar, and battery sources to meet varying power demands efficiently.

4. CONCLUSION & RECOMMENDATION

The deployment of hybrid solar-diesel systems for construction power in Indonesia represents a tangible step toward more sustainable and cost-efficient energy utilization. Through partial substitution of diesel generator operations with photovoltaic energy, construction projects can realize significant reductions in fuel consumption, maintenance frequency, and greenhouse gas emissions. The findings from the case study demonstrate that integrating 50% solar offset results in approximately 419,400 L/year fuel saving, IDR 6.3 billion/year cost reductions and 2,730 tonnes/year CO_2 reduction, with payback in under two years.

This approach enhances project sustainability performance, supports Indonesia's renewable energy commitments, and provides a replicable framework for future EPC projects. The hybrid model proves not only environmentally responsible but also economically viable when considering long-term operational benefits and reduced exposure to fuel price volatility.

The paper provides several recommendations to facilitate the effective deployment of hybrid solar-diesel systems on construction sites in Indonesia. These recommendations focus on overcoming implementation barriers, optimizing technical design, and ensuring alignment with broader sustainability goals.

Pilot and Scale-Up Deployment

Begin by implementing pilot hybrid systems, featuring photovoltaic arrays ranging from 30 to 50 kWp and batteries with a capacity of 100 kWh, at selected construction sites. These pilots will validate system performance and inform a subsequent scale-up plan targeting project with durations exceeding 12 months.

Leasing and Partnership Models

To address upfront investment barriers, adopt equipment leasing schemes or establish partnerships with solar equipment suppliers or EPC contractors. These approaches help to distribute capital costs and make the deployment of hybrid systems more financially accessible.

Centralized Energy Management

Develop a centralized solar asset management and monitoring program. This initiative will optimize the utilization of solar resources, streamline maintenance activities, and enhance the collection of data necessary for sustainability reporting.

Technical Optimization

Design containerized or foldable photovoltaic systems to accommodate limited space constraints

typical of active construction sites. Integrate automated hybrid controllers to enable seamless switching between solar, diesel, and battery power sources, ensuring efficient responses to varying load demands.

Policy and Corporate Alignment

Encourage alignment of project implementation strategies with national renewable energy roadmaps and corporate net-zero commitments. Consistent reporting of CO_2 savings and cost benefits across all projects supports these broader objectives and enhances transparency.

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Irwan has over 26 years of experience in the oil and gas industry, LNG and chemical plant projects, backed by a solid foundation as process engineer lead with 22 years of engineering experience. A certified professional engineer and ASEAN engineer combines deep technical knowledge, strategic leadership in execution planning, risk analysis and safety assurance. Currently assigned as the Commissioning Manager for the Tangguh UCC Project at BP Indonesia. Hold a bachelor's degree in chemical engineering from the University of Indonesia.

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Ir. Alisya Purnama Ramadhania, MEng, IPP possesses over 9 years of experience as a commissioning engineer, with a proven track record of successfully delivering complex projects smoothly during the commissioning phase. Consistently demonstrates expertise in understanding the sequence of execution, scheduling activities based on facility design limits, and overseeing the integration of operational readiness between new and existing facilities. Holds both a bachelor's degree and a master's degree in chemical engineering from the University of Indonesia. She is currently assigned as the Commissioning Process Lead for the Tangguh UCC Project at BP Indonesia.

Ir. H. Andhy Rachman, AMd



Ir. H. Andhy Rachman, AMd has nearly 30 years of proven experience in electrical installation, supervision, testing, commissioning, and start-up across major oil & gas (onshore/offshore), power generation, and electrical substation projects. He has an extensive track record managing commissioning team, ensuring safety integrity, safety compliance and handover readiness from fabrication yards to offshore operational sites. His background combines strong technical competence with leadership in multi-disciplinary environments and contractor/vendor interface management. He is currently assigned as the Commissioning Electrical Lead for the Tangguh UCC Project at BP Indonesia.

MENINGKATKAN INTEGRITAS TANKI TIMBUN KONDENSAT PADA DOUBLE-DECK FLOATING ROOF MELALUI ITAPM PROGRAM

Roni Hadi Wijaya, Dimas Muhammad Fawwaz, Rubi Herwin
Pertamina Medco E&P Tomori Sulawesi, Luwuk, Indonesia

ABSTRAK

Tanki timbun dengan *fluida* condensate di JOB Tomori merupakan *SECE Equipment* yang memiliki PdM cycle sebagai perencanaan pemeliharaan guna menjaga integritas dan kehandalan peralatan meruapakan elemen 9 PSAIMS. Dengan produksi *condensate* 6500 BOPD dan merupakan SECE dengan kategori process containment dan bila terjadi failure akan mengakibatkan risiko keselamatan (ledakan, kebakaran, release fluida dan isu lingkungan) yang merupakan PSE Tier 3 hingga Tier 1. Kegagalan pada tanki timbun dapat disebabkan oleh sambaran petir, kegagalan pada seals *floating roof*, korosi pada *shell course* dan *floating roof*, kebocoran bottom plate akibat katodik proteksi yang kurang baik serta mal-function pada peralatan pengaman (relief vent, breather valve, dll) dari tanki timbun. Program ITAPM *(Inspection, Testing, Assessment and Preventive Maintenance)* di kolaborasi dengan assessmen untuk melihat risiko dari tanki dengan kalkulasi PoF dan CoF, *effectiveness* proteksi penangkal petir serta katodik proteksi yang terpasang. Pemantauan mekanisme kerusakan yang di duga suspect dengan metode inspeksi dan testing (MFL, ECT, Plumbness, Settlement, UTM) dengan teknologi yang tepat sangat di perlukan dalam mendeteksi potensi kegagalan serta di dokumentasikan secara digital dalam TIAMS (Tomori Integrity Asset Management System) yang mudah di akses setiap pekerja. Hasil inspeksi dan *testing* di lanjutkan dengan assessment sebagai referensi untuk tindakan *preventive maintenance* untuk mencegah terjadinya kegagalan dalam operasi.

Kata Kunci: *tanki timbun*, *floating roof*, condensate, Integritas, *ITAPM program*

1. PENDAHULUAN

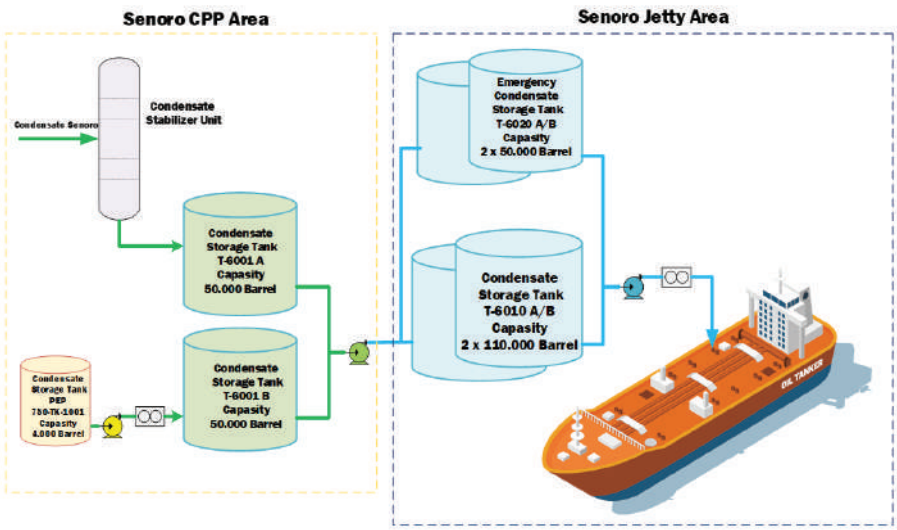
JOB Pertamina Medco Tomori Sulawesi memiliki CPP Senoro yang menghasilkan *condensate* yang diolah di condensate stabilization unit (CSU) untuk memperoleh nilai RVP yang sesuai spesifikasi. Di lapangan Senoro, JOB Tomori memiliki 6 (enam) Tanki timbun untuk penampungan condensate, 2 (dua) Tanki condensate storage dengan kapasitas 50.000 bbl terletak di CPP Senoro, 2 (dua) condensate loading tank dengan kapasitas 110.000 bbl dan 2 (dua) emergency condensate loading tank dengan kapasitas 50.000 bbl terletak di area jetty (Gambar 1. *Condensate Integration*).

Karakteristik konsentrasi fluida kondensat dan faktor lokasi tanki yang di operasikan berada di wilayah rawan gempa dan di area dekat lepas pantai yang memiliki korosifitas

yang tinggi diperlukan pemeriksaan, pengujian, assessment dan perbaikan terhadap temuan untuk mengembalikan integrity dari peralatan dan memastikan kesiapan *condensate storage tank* tersebut. Pemeriksaan tanki timbun dilakukan oleh inspektur yang memiliki kompetensi API 653.

2. METODOLOGI

Metode / strategi yang di gunakan untuk meningkatkan integritas *storage tank double-deck floating roof* setelah di operasikan selama 10 tahun dengan ITAPM *(Inspection, Testing, Assesment and Preventive Maintenance*) program; pertama dengan *Inspection and Testing*, kedua *Assessment*



Gambar 1. *Condensate Integration*

2.1. Data Teknis Condensate Storage Tank Double-Deck Floating Roof

Tabel 1. *Data Condensate Storage Tank*

Tank ID	T-6001 A	T-6001 B	T-6010 A	T-6010 A	T-6020 A	T-6020 B
Desain Code	*API 650 11TH edition 2011*					
Tipe Tanki	Above Ground Welded Steel Tank					
Deskripsi	Condensate Storage		Condensate Loading		Emergency Storage Tank	
Manufacture	PT. Bangun Bejana Baja					
Type Roof	*Double-Deck Floating Roof*					
Type Seal	*Primary Seal : Scissor shoe* *Secondary Seal : Seal King*					
Fluida	*Condensate*					
Working Capacity (bbl)	50.000		110.000		50.000	
Ukuran (mm)	30480 (ID) x 14630 (H)		42672 (ID) x 15240 (H)		30480 (ID) x 14630 (H)	
Material	A 283 gr. C	A 283 gr. C	A 283 gr. C	A 283 gr. C	A 283 gr. C	A 283 gr. C
Corrosion Allow. (mm)	1.5	1.5	1.5	1.5	1.5	1.5
No. of Shell Course	5 (lima)		6 (enam)		6 (enam)	
Peralatan Pengaman	*Foam Chamber, Water Sprinkle, Breather Valve, Emergency Relief Vent, Emergency Vent, Grounding, Bund Wall, Lighting Rod*					
Katodik Proteksi	SACP (Sacrificial Anode Cathodic Protection)					
Lokasi	CPP Senoro		Jetty		Jetty	
Tahun Pembuatan	2015		2015		2015	

dan ketiga dengan *Preventive Maintenance.*

2.2. Inspection & Testing – NDE

a. Pemeriksaan Internal Tanki

- Pemeriksaan visual *internal storage tank* meliputi; ruang pontoon (Compartment), roof deck support, *piping drain system*, drain line flexible connection, *mechanical scissor, secondary seal, drain sump,* roof shell and bottom inside, sump tank, critical zone, coating.
- Pengujian tak rusak: *Magnetic Flux Leakage (MFL),* UT bottom plate, Vacuum Box, Eddy Current Testing (ECT) pada annular plate.

b. Pemeriksaan Eksternal Tanki

- Pemeriksaan visual kondisi eksternal *storage tank* meliputi; Pondasi, *Projection plate, nozzle-flange & manway-flange, shell course, floating roof,* peralatan pengaman *(Venting, Breather valve, foam chamber, emergency vent, Rim Vent), Rim Seal dan Secondary Seal, stair & handrail, platform & grating, fire water piping, wind girder,* painting.
- Pengukuran ketebalan nozzle, shell course & roof, katodik proteksi, *grounding system, Roundness, plumbness dan Settlement*
- Pengujian tak rusak: Eddy Current Testing (ECT), Vacuum Box pada Roof.

2.3. Assessment

a. Assessmen berbasis risiko dengan melakukan kalkulasi CoF dan PoF dari *storage tank.*

b. Assessmen terhadap sistem proteksi terhadap petir.

c. Assessmen pada sistem katodik proteksi.

d. Remaining Life Assessment, perhitungan laju korosi dan rencana next internal inspeksi.

2.4. Preventive Maintenance

Program perbaikan dilakukan untuk mengembalikan integritas dari peralatan sesuai dengan standard / code dan desain kontruksi Tanki timbun:

a. Melakukan perbaikan *bottom plate* yang memiliki ketebalan kurang dari nilai MRT (*Minimum Required Thickness*)

b. Melakukan uji tak rusak (NDE) dengan Penetrant atau Magnetic pada lokasi pengelasan

c. Melakukan penggantian Rim Seal dan Secondary Seal yang mengalami kerusakan

d. Melakukan Re-design katodik proteksi agar memiliki nilai minimal proteksi > -850 mV

3. HASIL DAN DISKUSI

3.1. Inspection and Testing – NDE

Pemeriksaan storage tank dilakukan mengikuti API standard 653 dengan format checklist untuk inspeksi tanki sesuai dengan Annex C dan inspector kompetensi sertifikasi API 653 dengan rencana pemeriksaan dan pengujian sesuai **Tabel 2**.

a. Pemeriksaan Internal Tanki

Pemeriksaan internal storage tank dilakukan pada saat kondisi tidak beroperasi, dipastikan telah diisolasi dari product dan elektrikal power, telah bersih dan bebas gas, aman untuk masuk untuk bekerja dan memiliki penerangan yang memadai. Pemeriksaan di lakukan dengan 2

Tabel 2. *Perencanaan Inspection Condensate Storage Tank – Double deck Floating Roof*

Tank ID	External Inspection						Internal Inspection						
	Vis. Insp	UT	Plumb ness	Round ness	Settle ment	CP	Vis. Insp	UT	MFL	Vac. Box	ECT	PT MT	RT
T-6001A	√	√	√	√	√	√	√	√	√	√	√	√	-
T-6001B	√	√	√	√	√	√	√	√	√	√	√	√	-
T-6010A	√	√	√	√	√	√	√	√	√	√	√	√	√
T-6010B	√	√	√	√	√	√	√	√	√	√	√	√	-
T-6020A	√	√	√	√	√	√	√	√	√	√	√	√	-
T-6020B	√	√	√	√	√	√	√	√	√	√	√	√	-

metode:

- Pemeriksaan Visual

  Pemeriksaan visual meliputi: *floating roof leg* dan *leg pad*, *floating roof pontoon compartments*, ukuran cacat/temuan *(pitting)*, *marking* dan catat semua patching, periksa dan buatlah sketch korosi, *record bottom layout sketch*, periksa *floating roof supports*, *floating roof seals assembly*, periksa *closed drain system* termasuk *flexible pipe drain, articulated joint drain, fixed drain line*, periksa akses struktur (*handrail, platform frame, deck plate dan grating, stairways, rolling ladder*)

- Pengujian Tak Rusak (NDE)

  Pengujian NDE meliputi: UT ketebalan,



Gambar 2. *Pemeriksaan Internal Storage Tank*

Magnetic Flux Leakage (MFL), Vacuum Box pada bottom plate, Pemeriksaan Eddy Current Testing (ECT) pada annular plate

b. Pemeriksaan Eksternal Tanki

- Pemeriksaan visual

  Pemeriksaan visual meliputi: foundasi, kondisi coating *(holes, disbanding, deterioration, discoloration*), marking area *patching* (jika ada), pengukuran pitting, periksa perangkat pengaman *(breather valve, vents, emergency P/V hatch*, periksa floating roof pontoon, roof deck, floating roof appurtenance, primary dan secondary seal.

- Pengujian Tak Rusak (NDE)

Pengujian tak rusak meliputi: UT ketebalan (*shell course, roof, nozzle* dan manways), pengukuran katodik proteksi, *grounding system*, Pengukuran *roundness, plumbness, settlement, Vacuum Box* pada Roof, *eddy current testing (ECT)* pada annular plate

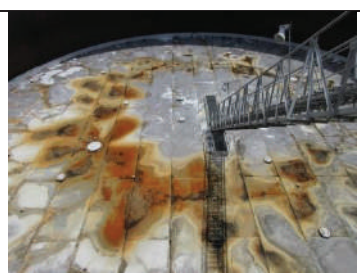
c. Hasil Pemeriksaan dan Pengujian Storage Tank

Berikut hasil inspection, testing dan assessment yang telah di lakukan dalam Tabel 3.

3.2. *Assessment*

a. Risk Based Inspection (RBI) Assessment

Analisa risiko terhadap *storage tank* menggunakan standard/Code API 581 dengan Risk Matrix 5x5 di tunjukkan hasil dalam **Tabel 4.**

<table>
<tr>
<td>
General View T-6020A</td>
<td>
Floating roof terkorosi</td>
<td>
Pengukuran plumbness</td>
</tr>
<tr>
<td>
Celah di projection plate</td>
<td>
Kerusakan pada seals</td>
<td>
Vacuum box on Roof plate</td>
</tr>
</table>

Gambar 3. *Pemeriksaan Eksternal Storage Tank*

Tabel 3. *Hasil Inspection, Testing dan Assessmen*

EXTERNAL INSPECTION	INTERNAL INSPECTION
• Cacat sobek pada terpal *seal floating roof* • Celah di *projection plate*, air masuk • Tanki tidak ter-proteksi katodik proteksi • Medium Korosi pada *floating roof* • Beberapa nozzle mengalami korosi di *flanges* • *Rim vent* terdapat banyak kotoran • Terdapat celah antara dinding *shell* dan *seal* • Terdapat kotoran pada *foam chamber*	• *Ponton compartment* terisi air • *Korosi bottom plate* pada *soil side* • Terjadi *pitting* pada *internal shell* • *Support roof leg* menggantung • *Internal coating* menggelembung • *Karet seal manways* rusak

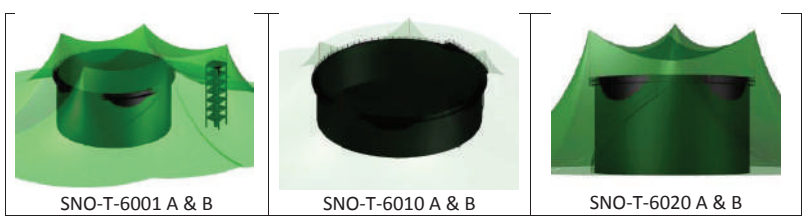
Assessment terhadap sistem proteksi terhadap petir

Lokasi JOB Tomori berada di khatuliswa dengan kepadatan sambaran petir yang tinggi, berkisar 20-40 strikes/km2/tahun, potensi bahaya sambaran petir diperlukan perbaikan sistem proteksi penangkal petir yang handal sesuai IEC 62305. Semua tanki telah dilengkapi penangkal petir, namun untuk *floating roof* tank badan tanki tidak dapat digunakan sebagai konduktor turun alami, ini disebabkan tanki tidak tertutup rapat (Gambar 4.) sehingga memungkin munculnya percikan api yang dapat membahayakan Tanki.

Hasil assessment disarankan proteksi petir standar mekanisme “fire triangle”, mencegah terjadi loncatan bunga api pada celah di atap tanki, mencegah aliran arus petir melalui Tanki logam, permasangan terminal udara pada ujung dinding tanki dengan penghantar

Tabel 4. *Risk Assessment Storage Tank*

No	Lokasi	Tank ID	Description	CoF	PoF	Risk	Remarks
1	CPP	T-6001 A	*Condensate Storge Tank A*	5	3	35	High
2	CPP	T-6001 B	*Condensate Storge Tank B*	5	3	35	High
3	Jetty	T-6010 A	*Condensate Loading Tank A*	5	3	35	High
4	Jetty	T-6010 B	*Condensate Loading Tank B*	5	3	35	High
5	Jetty	T-6020 A	*Emergency Condensate Storage Tank A*	5	3	35	High
6	Jetty	T-6020 B	*Emergency Condensate Storage Tank B*	5	3	35	High



Gambar 4. *3D Rolling Sphere Existing Tanki Timbun*

turun terpisah dari dinding Tanki, gunakan Lorentz Grounding LPS II terpasang perbaikan ke LPS I.

2) Assessmen katodik proteksi

Pengukuran katodik proteksi menunjukkan potensial struktur lebih positif dari -850 mV (tidak terproteksi) dan dibutuhkan Re-design CP untuk T-6010 dan T-6020 dengan hasil berikut;

- ✓ Soil resistivity testing menunjukkan tingkat korosi tanah sangat korosif dengan nilai pengukuran 0-500 ohm-cm untuk T-6010 A/B dan T-6020 A/B
- ✓ Insulation join testing menemukan semua flanges tidak terpasang insulation
- ✓ Eksisting katodik proteksi menggunakan SACP (Sacrificial Anode Cathodic Protection) dan pada saat pengukuran potensial anode dan pipa tidak terhubung

Berdasarkan CP assessment, Tanki T-6010 dan T-6020 disarankan untuk pemasangan ICCP.

3) Perhitungan laju korosi dan estimasi sisa umur (RLA)

Berdasarkan hasil pemeriksaan ketebalan bottom plate, korosi terjadi pada bottom plate di mana minimum yang persyaratkan adalah 0.1 inchi atau 2.54 mm pada inspeksi internal berikutnya maka perhitungan interval internal inspeksi berikutnya (Or) di hitung dengan formula MRT.

$$MRT = (Minimum\ RTbc\ atau\ RTip) - Or\ (StPr + UPr)$$

Hasil perhitungan laju korosi dan estimasi remaining life di tampilkan dalam Tabel 5. Berikut

Remaining life dalam **Table 5**. diatas didapat dari ketebalan bottom plate dengan nilai MRT 2.54 mm

Tabel 5. *Laju Korosi dan Remaining life*

NO	LOKASI	TANK ID	NEXT INTERNAL INSPECTION (OR)	LAJU KOROSI (MMPY)	REMAINING LIFE (YEAR)	REMARKS
1	CPP Senoro	T-6001 A	18 yr	0.144	35	
2	Jetty Senoro	T-6010 A	15 yr	0.15	32	
3	Jetty Senoro	T-6010 B	10 yr	0.3	15	
4	Jetty Senoro	T-6020 A	10 yr	0.5	14	
5	Jetty Senoro	T-6020 B	10 yr	0.2	15	

3.3. Preventive Maintenance

Elemen 9 - PSAIM (Process Safety dan Asset Integrity Management) menjalankan perbaikan dan perawatan peralatan yang cacat dengan prioritas pada peralatan SECE untuk memastikan peralatan tersebut berfungsi dengan baik telah di lakukan tindakan berikut:

a. Melakukan perbaikan bottom plate dengan *metal loss > 30%.*

b. Melakukan pengujian dengan Uji Penetrant pada lokasi pengelasan

c. Melakukan penggantian *Rim Seal* dan *Secondary Seal* yang mengalami kerusakan

d. Melakukan Re-design katodik proteksi pada Tanki T-6010 dan T-6020 dengan system *ICCP.*

Aktivitas *inspection, testing dan preventive maintenance* tersimpan dalam TIAMS (Tomori Integrity Asset Management System) dan dapat di akses oleh semua pekerja.

4. KESIMPULAN

Korosi *bottom plate condensate storage tank* terjadi pada soil side disebabkan kurang efektifnya katodik proteksi, air yang masuk dari projection plate dan pondasi Tanki. Hasil assessmen katodik proteksi disarankan menggunakan sistem ICCP (Impressed Current Cathodic Protection) untuk meningkatkan nilai proteksinya.

Perlindungan struktur terhadap petir berdasarkan assessmen disarankan untuk menggunakan penghantar turun terpisah dari dinding Tanki, gunakan Lorentz Grounding LPS I.

Rim seal maupun secondary seal setelah 10 tahun pemakaian di perlukan perencanaan penggantian dan pemasangannya dapat dilakukan pada saat internal inspection Tanki.

Ponton compartment dapat tergenang air menyebabkan korosi dan membuat *floating roof deck* miring, di perlukan pengecekan rutin sistem drainase berfungsi, pastikan *drain valve normally open.*

TENTANG PENULIS

Roni Hadi Wijaya, ST, MSi



Roni Hadi Wijaya, S.T, M.Si seorang angota IAFMI Bidang Keahlian Mechanical Static dan Pipeline (23.121) dengan lulusan Diploma Teknik Mesin UPN Veteran Jakata, sarjana Teknik Mesin dari ISTN Jakarta dan Magister Ilmu Material dari Universitas Indonesia yang memiliki pengalaman di industri Minyak dan Gas Bumi selama lebih dari 26 tahun dan posisi saat ini Sr. Asset Integrity Engineer dengan memulai karir sebagai Mechanical Inspector, Inspection Engineer, RBI Engineer, RBI Analis dan Facility Integrity Engineer.

Dimas Muhammad Fawwaz, ST



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Rubi Herwin, ST



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OILFIELD DEVELOPMENT STRATEGY OPTIMIZATION USING RISK-BASED APPROACH IN NORTH AREA OF OFFSHORE SOUTHEAST SUMATERA

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ABSTRACT

Holding 6th position as biggest oil producer in Indonesia, PHE OSES commit to maintain its production rate to be aligned with Subholding Upstream, SKK Migas, and President Prabowo Asta Cita for Energy Self-Sufficiency. PHE OSES have development plan spreading in all of its working areas, i.e. North, Central, and South to maintain the baseline and increase the production at the same time.

The development plan in North Area involving side track and horizontal drilling leveraging existing well slot and platform using jack up rig. The target platform is a production platform with two Gas Turbine Generator (GTG) installed which are critical for electricity supply in North Area. This condition makes the risk assessment more complex, hence the rigorous study is conducted considering many aspects including the jack up rig approach direction, potential for simultaneous operations (SIMOPS) and potential for Loss of Production Opportunity (LPO) with ultimate intent to find the best way to execute the development plan in a safe manner. Otherwise, the other means of development should be prepared.

Thorough risk-based evaluation is provided for the management as the basis for decision making. Process safety risks arise from SIMOPS between jack up rig approach and GTG running is high, while the trade-off with platform shutdown will impact LPO in enormous amount that equal to seven times of PHE OSES daily production. The alternative development plan is proposed using another platform in the vicinity area which is deemed less complex from surface facility perspective resulting in safer approach

Keywords: Development Plan, Risk-based Evaluation, LPO (Loss of Production Opportunity)

INTRODUCTION

According to Oil and Gas Directorate General 2024 report, PT. Pertamina Hulu Energi Offshore Southeast Sumatera (PHE OSES) subsidiary of Subholding Upstream PERTAMINA, rank as 6th largest Oil Producer in Indonesia. PHE OSES operates Southeast Sumatera (SES) block, one of the most mature offshore oil fields in Indonesia with long history of production sharing contract. Developed in the early 1970s, SES Block consists of three areas namely North, Central, and South.

PHE OSES commit to maintain its production rate to be aligned with Subholding Upstream and SKK Migas Objective, and President Prabowo Asta Cita aspiration for Energy Self-Sufficiency. It reflected in the development plan that spreading in all areas to maintain the baseline and increase the production at the same time.

One of the development plans in North area face the challenging situation. The target platform where the existing slot will be used for horizontal drilling using jack up rig, have been modified by previous operator with additional installations of two Gas Turbine Generator (GTG) for supplying electricity, not only for this platform but also for North Area. Mature field rely heavily on electricity mainly because its dependency on artificial lift, i.e. Electric Submersible Pump (ESP) to produce oil and gas. Therefor, electricity plays pivotal role and become a backbone for hydrocarbon production.

SIMOPS matrix during rig approach dictate that the platform shall be in shut down condition. Regarding the after mentions above, shut down the platform while maintaining the GTG running seemed as a good option and need to be evaluated further whether is it possible from jack up rig approach requirement or not. The risk assessment on surface facility then conducted to provide management with decision-making support package to ensure that all risk, both operational and business risk, already considered.

CONSTRAINT

Intense discussion with drilling team is initiated to ensure the final approach direction of Jack up Rig, considering the facility layout, adjacent platforms, seabed conditions, and cantilever coverage. Rigorous assessment concludes that the approach only possible from north, which increase

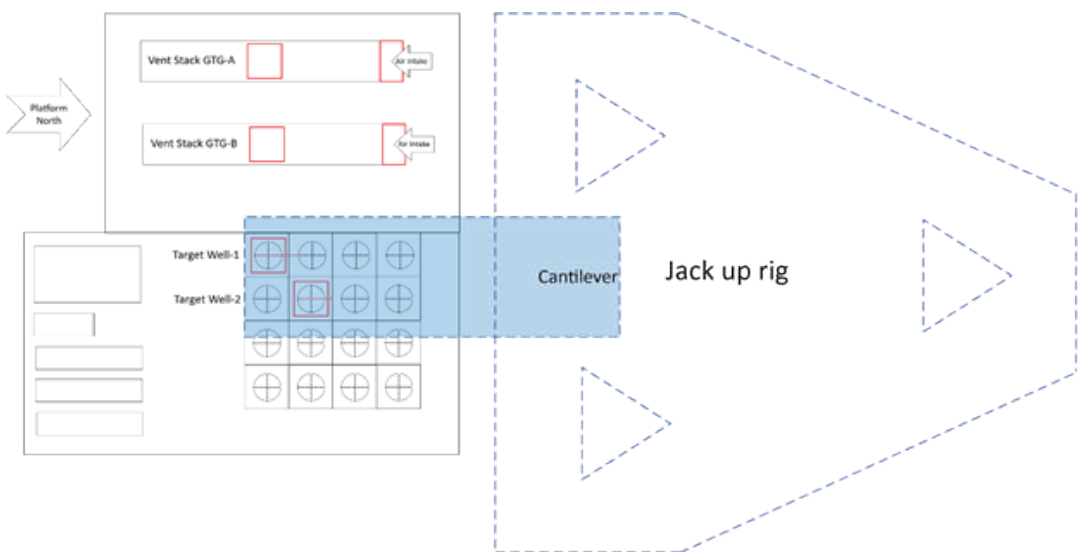


Figure 1. *Illustration of Main Deck Layout on Target Platform for Jack Up Rig Activity (not to scale)*

the complexity of approaching procedure. The rig's cantilever will be above the GTG including its vent stack and air intake. Some options then evaluated qualitatively, mainly to assess the risk during two step, rig approach while platform is running and GTG simultaneous operation during drilling activity. The options are depicted using evaluation tree as follow:

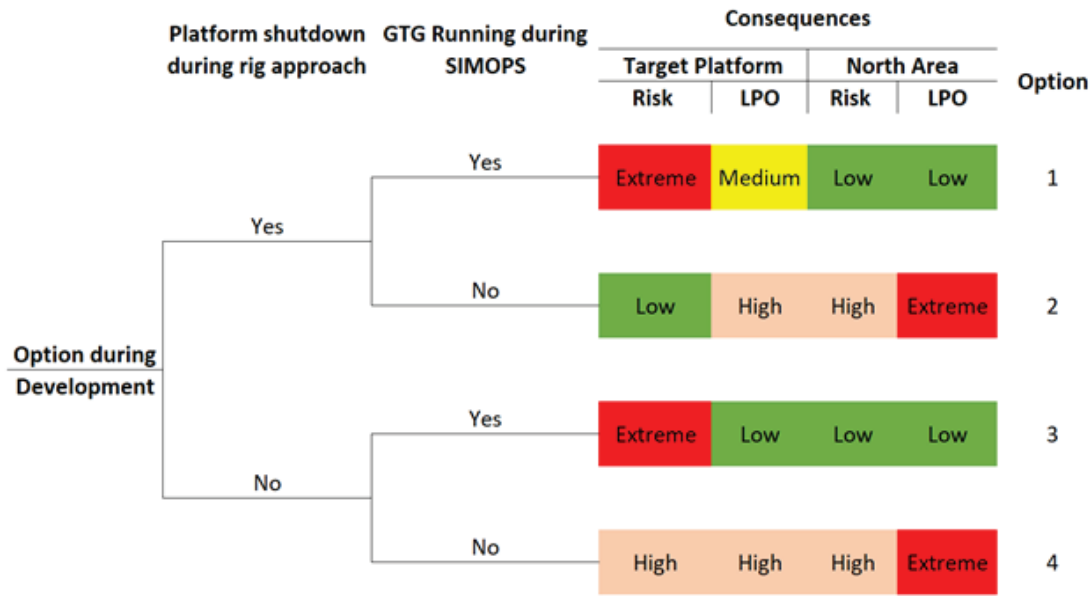


Figure 2. *Risk-based Evaluation Tree*

The consequences are divided into two specific locations, target platform and north area with two main parameter, risk which is represent process safety risk, i.e. fire/explosion and LPO that represent business risk. These two main drivers need to be balanced and need further assessment, especially risk and potential for LPO which hold the "Extreme" category.

Option 1 and option 3 have low LPO but Extreme risk on target platform due to:

1. Potential collision between Platform and jack up rig. This scenario can occur during approach or during progressing to final position (due to punch through or leg sliding). Keeping platform alive will exacerbate the conditions if the collision occurred regarding the hydrocarbon inventory and operating conditions. Potential consequences are hydrocarbon loss of containment, fire/explosion if ignited, resulting in multiple fatalities, asset damage, environmental issues (oil spill), and reputations.
2. Simultaneous operations of GTG while drilling activity with highly potential of fire/explosion due to hydrocarbon ingress into air intake GTG, or hot flue gas act as ignition source when reaching rig floor. The potential consequences will be multiple fatalities, asset damage, environmental issues (oil spill), and reputations.

On the other hand, option 2 and 4 relatively has lower risk compared to other options. However, the potential LPO is extreme. The horizontal drilling will require more than 2 months of platform shutdown, resulting in extreme LPO. With requirement to start up and ramp up production, total LPO is estimated equal to a week of PHE OSES production capacity.

This paper will discuss mainly on Risk aspect to determine whether the options is possible or not, specifically on potential SIMOPS between GTG running and drilling activities (option 1). The options 3 is eliminated due to restriction from Rig owner to conduct rig approach during live platform.

ASSESSMENT

Qualitative assessment is carried out to identify potential hazard when SIMOPS. HAZID methodology is use to identify and assess the risk.

Table 1. *Hazard Identification*

ITEM NO.	HAZARD TYPE	GUIDEWORD CATEGORY	GUIDEWORDS	POSSIBLE Causes/Concern	CONSEQUENCES
1	**Specific Guideword - SP**	Rig Activity during GTG is running	1. Outer deck position	Cantilever (including drilling floor) will be directly above GTG vent stack with estimated temperature 485 deg.C	Potential for extreme heat exposure from GTG vent stack to drilling floor which potentially contained hydrocarbon during drilling activity, act as ignition source, causing potential fire/explosion resulting in multiple fatalities, asset damage, large oil spill, and bad reputations
2			2. Hydrocarbons are present on drilling floor during drilling activities	Air intake from GTG location face directly toward drilling floor	Potential hydrocarbon on rig floor is flowing into air intake of GTG, being compressed, and mixed with high temperature, causing potential for fire/explosion resulting in multiple fatalities, asset damage, large oil spill, and bad reputations

A simulation is required to confirm the potential consequences, including the heat coverage from vent stack. This simulation will determine the heat radius, whether or not it can reach the critical receptors in the vicinity and its potential impact. The potential impact to receptors is defined as impairment criteria, with temperature as main parameter. Two critical receptors are identified during HAZID, workers on the rig floor, and the hydrocarbon on the rig floor during drilling activity.

Workers are relatively sensitive to temperature since the work load is high. This condition worsens by the high relative humidity in offshore environment, make the Wet Bulb Temperature Index (WBTI) higher. Theoretically, maximum WTBI that human can safely work is at 35 ^{0}C, above this value, there is a potential for experiencing heat illness, i.e. heat stroke, that can lead to fatality if not managed properly.

Rig floor possess more severe consequences. With potential hydrocarbon vapor exist during drilling activity, extremely high temperature from vent stack can trigger fire and/or explosion if the Auto Ignition Temperature (AIT) achieved.

The simulation then conducted using available software with main objective to obtain the heat contour resulting from flowing flue gas outlet GTG vent stack, specifically GTG-B which is closer to the jack up rig. The result shows that heat contour in the vicinity of target well is still much higher than

Table 2. *Critical Receptors and Impairment Criteria*

NO.	CRITICAL RECEPTORS	CONCERN	IMPAIRMENT CRITERIA (^{0}C)	REMARKS
1	Workers	Potential for Heat stroke	50	Threshold limit value for workers is defined in term of Wet Bulb Temperature Index (WBTI) as function of humidity and work load. Theoretically, maximum WTBI for workers is 35 ^{0}C
2	Rig floor	Potential for fire/explosion when Auto Ignition Temperature (AIT) is reached	450	Methane as major component is taken as reference for Auto Ignition Temperature

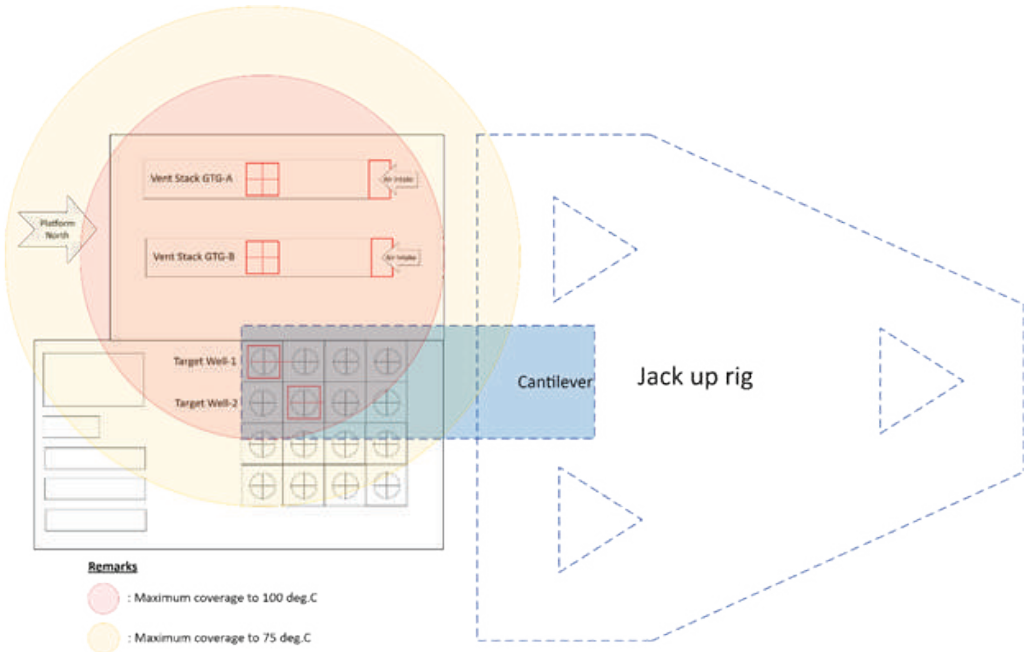


Figure 3. *Illustration of Heat Exposure for Critical Receptors*

impairment criteria (50^{0}C). The sensitivity analysis using temperature reference at 100^{0}C and 75 ^{0}C confirm the potential coverage area, ranging from 20m to 35m, respectively. For the temperature maximum 50^{0}C, the working area should be on the outer of the existing deck, which is impossible to achieve without any additional extension deck. The complete result is depicted below.

All of the option has extreme risk, option 1 and 3 on operational risk (process safety risk) while option 2 and 4 on business risk (potential for LPO). The trade-off between these two types of risk is hard to achieved and deemed not feasible with the risk remains not tolerable. Hence the development strategy needs to be optimized and seek the alternative.

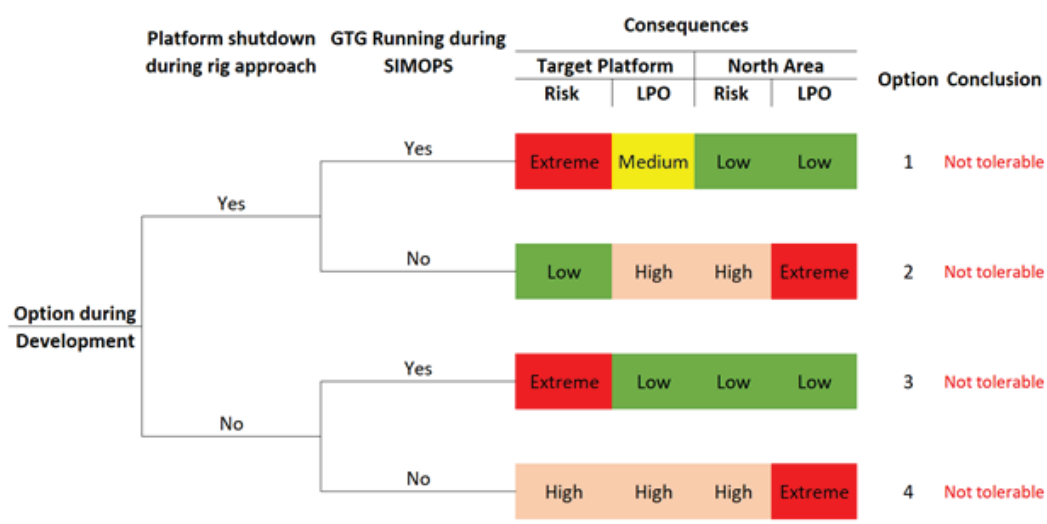


Figure 4. *Conclusion of Risk-based Evaluation Tree*

After careful consideration from the sub-surface point of view, the drilling plan will be conducted from other platform which has less complexity, lower production rate, and independent from electricity grid but still on the same sub surface structure area.

The thorough assessment in early stage of the project can optimize the development strategy in the oilfield, balancing the operational and business risk to maximize the production while reducing the risk at the same time. Risk-based approach can help management in decision making to seek the most safe and feasible strategy.

CONCLUSION AND RECOMMENDATION

1. Rigorous assessment is required to ensure the safe and reliable operability by balancing the operational risk (process safety risk) and business risk (potential LPO).
2. Risk assessment conducted on earlier stage of the project will avoid operational problem with minimum cost, which in turn support the operational sustainability to achieve energy resilience in the future.
3. Risk-based approach that communicate clearly will act as an excellent source to help management in decision making to deliver safe and feasible operation.

ACKNOWLEDGEMENT

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EVALUATION OF ADVANCED MOTOR STARTING TECHNIQUES FOR HIGH-POWER INDUSTRIAL APPLICATIONS: **MITIGATING ELECTRICAL, THERMAL, AND MECHANICAL STRESS THROUGH VARIABLE SPEED DRIVE INTEGRATION**

Nobal Ardhinata Rahadyan, Andrian Fauzi Halim and Muhammad Farhan Naufal Akbar
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ABSTRAK

This study investigates motor starting methods to minimize electrical, thermal, and mechanical stress in a 2380 kW, 3.3 kV induction motor that starts twice daily and can disturb grid stability. It evaluates the limitations of the conventional Korndorfer autotransformer starter, which applies 90% rated voltage but can create hazardous switching transients during its three-stage sequence. These transients may cause voltage surges, flashover, arcing, and insulation breakdown, reducing motor reliability. Based on failure analysis of a real incident, switching transients are identified as the main cause of dielectric failure, while high rotor bar current during inrush produces thermal stress and mechanical degradation. Using PSIM and ETAP simulations, the study compares the autotransformer with Variable Voltage Constant Frequency (VVCF) soft starters and Variable Voltage Variable Frequency (VVVF) Variable Speed Drives (VSD). Results show the autotransformer draws about 4x FLA, the soft starter about 3x FLA at 60% initial voltage, and the VSD only 1x FLA, significantly improving reliability, efficiency, equipment life, and grid stability..

***Keywords*:** motor starting, autotransformer, switching transient, soft starter

1. INTRODUCTION

Three-phase induction motors are widely used in industrial facilities due to their robustness and efficiency. However, starting large medium-voltage motors (e.g. 3.3 kV, 50 Hz) can produce inrush currents up to 6 times the full-load current under direct-on-line (DOL) conditions, causing voltage dips, mechanical stress, and potential grid instability in systems with limited short-circuit capacity. These phenomena may lead to process upsets, nuisance trips, and accelerated ageing of electrical equipment. To reduce starting current and torque, many high-power drives employ reduced-voltage starters. The Korndörfer autotransformer starter is a classic solution that lowers the motor terminal voltage using a tapped autotransformer. In a 3.3 kV system with a 90% tap, the starting voltage is reduced to 2.97 kV, lowering the starting current to approximately

65% of the DOL value and providing around 81% of DOL torque. This makes it attractive for high-torque loads such as pumps and compressors. Korndörfer's design, patented in 1914, uses a three-stage sequence: (1) reduced-voltage start through the autotransformer, (2) a transition stage where the autotransformer acts as a series reactor, and (3) full-voltage operation. This scheme was intended to limit open-circuit transients and reduce voltage spikes.

Industrial experience, however, shows that medium-voltage autotransformer starters can suffer significant failures. A 1993 Shell Oil presentation noted that 26% of Korndörfer starters installed after 1985 experienced major electrical failures, frequently involving layer-to-layer breakdown in transformer windings. These failures are strongly associated with switching surges created during transition, particularly when motors are started frequently and system impedance is high. In Refinery Unit II Dumai, the largest motor is a 2380 kW, 3.3 kV induction motor (140-PM-17) started approximately twice per day to drive a high-pressure pump. The existing Korndörfer autotransformer starter has experienced repeated failures, both electrical (flashover and winding short circuits) and mechanical (broken rotor bars and end rings). These events threaten plant availability and increase maintenance costs. This paper evaluates the existing autotransformer starter and compares

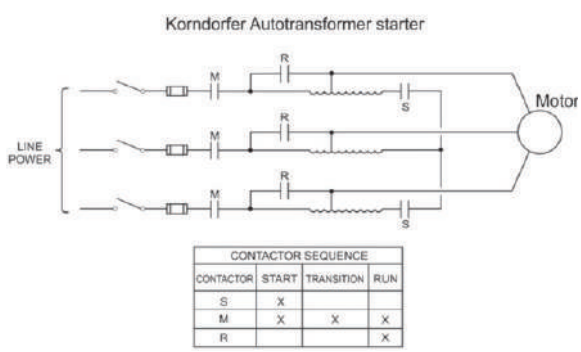


Figure 1. Auto Transformer Motor Starter (Asmoro, 2017)

it with two advanced starting methods: Variable Voltage Constant Frequency (VVCF) soft-starter control and Variable Voltage Variable Frequency (VVVF) control using a Variable Speed Drive (VSD). A detailed motor–autotransformer model is built based on manufacturer test data, validated against relay waveforms, and used in PSIM and ETAP simulations. The objective is to identify a starting method that minimizes electrical, thermal, and mechanical stress while improving system reliability and grid stability.

2. FAILURE ANALYSIS BACKGROUND

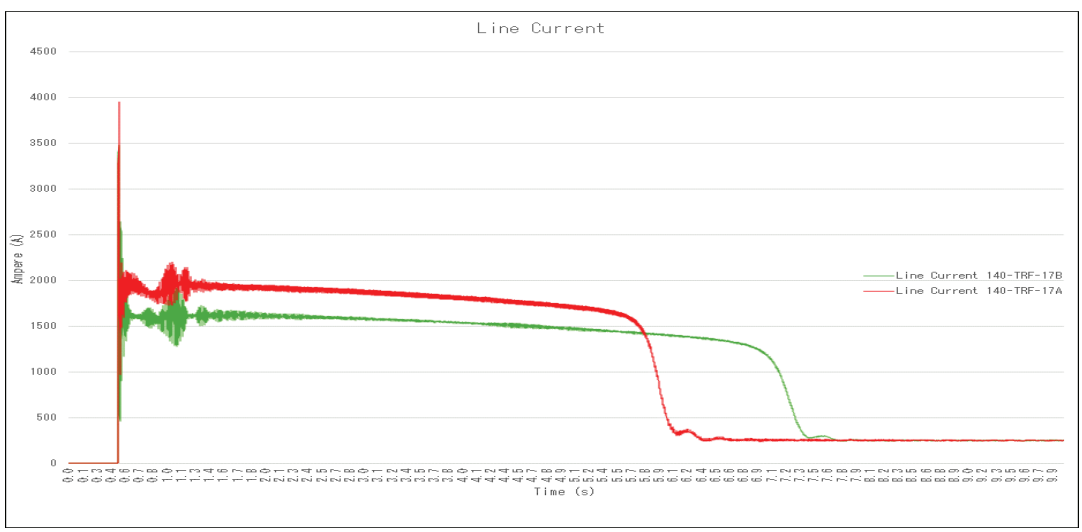
A detailed inspection of the autotransformer starter revealed flashover marks at the base of a red ribbed support insulator mounted on a metallic structure. The arc trace indicates a high-voltage discharge path initiated during autotransformer transition. Reduced dielectric clearance and proximity to grounded metal likely intensified the local electric field and triggered breakdown. Motor protection relay records show that the first starting stage produces a normal, balanced inrush. However, during the third stage, a sharp current spike exceeding 1000 A appears in one phase. This zero-sequence current component activates the ground-fault relay and leads to an unintended trip of Substation No. 4. The event confirms that switching transients do not only stress internal insulation but can also compromise external interfaces and disturb protection coordination. Switching surges arise from abrupt changes in circuit impedance and the release of stored magnetic and electric energy during transition from reduced to full voltage. Residual flux in the autotransformer and motor core, combined with magnetic hysteresis, can amplify these surges when switching is not synchronized with the voltage waveform. Capacitive couplings and cable capacitance further shape the transient waveform.

Sweep Frequency Response Analysis (SFRA) on the autotransformer identifies a resonance

peak around 1.27 MHz, defined by the combined inductance and capacitance of the winding structure. If the frequency content of a switching transient overlaps this natural frequency, the surge amplitude can be significantly magnified, increasing the risk of winding overvoltage and partial discharge. Most rotor-related faults in squirrel-cage induction motors involve broken bars and end rings. These failures are driven by combined thermal, magnetic, mechanical, and environmental stresses. Rotor fatigue cannot be attributed solely to mechanical stress; temperature distribution within the rotor is a dominant factor. For the 140-PM-17 motor, frequent starting with a 90% voltage tap reduces inrush current compared to DOL but still maintains a high starting current, typically around 5.4–7.2 times FLA. The thermal energy generated in the rotor is proportional to I^2t. Extended acceleration time at high current increases rotor temperature, causing thermal expansion of the bars and end rings. If expansion is constrained, significant thermal stress is generated. Two motors (140-PM-17A and 140-PM-17B), operated alternately, have exhibited similar failure patterns: rotor bar cracks, winding damage, shaft and bearing failures, and repeated breakdowns over the last decade. In parallel, the associated 905-TRF-17B autotransformer has suffered multiple internal short circuits with severe terminal and winding damage, even after full rewinding and refurbishment.

3. FAILURE ANALYSIS BACKGROUND

The studied motor is a 3-phase, 2-pole, 50 Hz, 3.3 kV induction motor rated 2380 kW at 2980 rpm with F-class insulation and a rated current of 470 A. Locked-rotor and no-load test data from the manufacturer are used to derive the equivalent circuit parameters. The driven equipment is a high-pressure hydraulic jet pump rated 2094 kW at 3650 rpm, connected through a gearbox with mechanical efficiency of 98.8%. The autotransformer starter has a through-put rating of 14.71 MVA, a no-load ratio of 3300/2970 V (90% tap), short-circuit impedance of about 2%, and ONAN cooling. Routine no-load and short-circuit tests provide magnetizing and leakage parameters used to represent the autotransformer in the simulation model. A complete motor–autotransformer–grid model is built in PSIM, with motor parameters derived from equivalent-circuit calculations and autotransformer parameters from test data. Digital relay waveforms captured during real starts are used to validate the model. The simulation reproduces the measured inrush current profile with good agreement and provides a reliable platform to evaluate alternative starting methods.



4.

Figure 2. Full Swept Waveform Autor Transformer Starting from Protection Relay

COMPARATIVE ASSESMENT OF STARTING METHODS

The Variable Voltage Constant Frequency (VVCF) method reduces stator voltage at constant frequency using a soft starter. Simulation shows that for initial voltages below 60% of nominal, the developed torque is insufficient to overcome pump breakaway torque, leading to stall. Even at 60–65% voltage, acceleration is slow and starting current remains above FLA for an extended period. Reactive power absorption increases rapidly and voltage stability is poor. The Variable Voltage Variable Frequency (VVVF) method, implemented via a VSD with scalar V/f control, maintains an approximately constant V/f ratio. Simulations indicate that with a 60-second linear ramp of both voltage and frequency from 0 to nominal, RMS current is only about 40% of FLA. This extremely low starting current minimizes rotor heating, I^2t stress, and mechanical shock. Reactive power remains close to rated and voltage flicker is practically eliminated. A comparative summary shows that the autotransformer and the VVCF soft-starter both produce high RMS starting currents (> FLA), large reactive power demand, and unstable voltage and frequency responses. In contrast, the VVVF VSD method keeps peak current below FLA, greatly reduces rotor heating, and eliminates switching surges, providing the best overall performance.

5. CONCLUSION

A detailed failure analysis of the 2380 kW, 3.3 kV induction motor and its Korndörfer autotransformer starter in Refinery Unit II Dumai shows that switching surges during autotransformer transition can initiate flashover and create high-frequency overvoltage near the autotransformer's resonance, leading to dielectric breakdown and repeated failures. High starting currents and long acceleration times generate substantial rotor I^2t, causing thermal stress, fatigue, and broken rotor bars and end rings. Frequent starts with insufficient cooling further accelerate damage.

The existing autotransformer and the alternative VVCF soft-starter both produce high RMS starting currents and poor voltage stability, with rotor heating exceeding allowable limits by nearly four times. The VVVF VSD method maintains an almost constant V/f ratio, limits

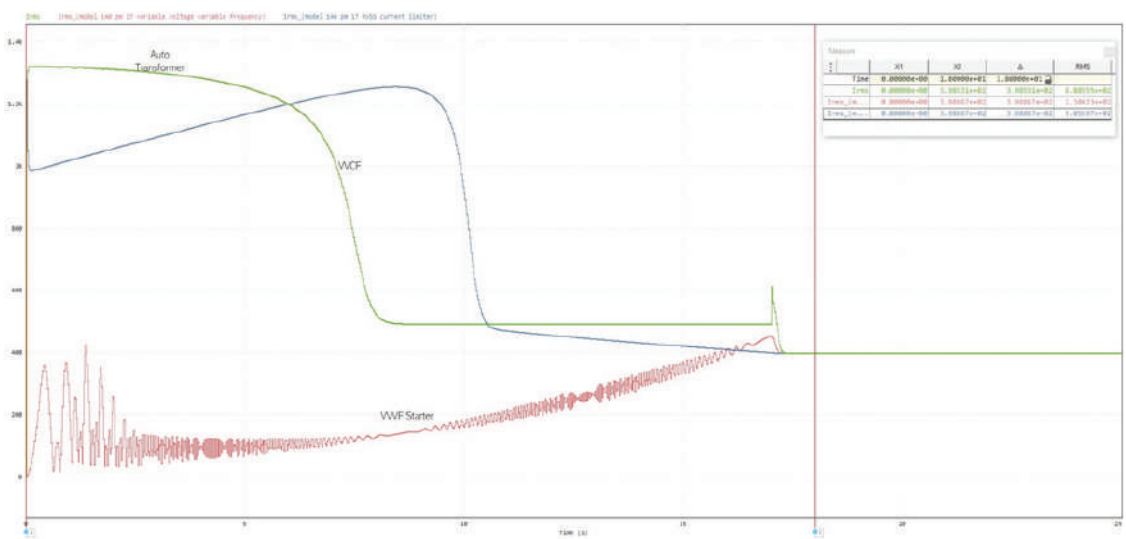


Figure 3. Full Swept Waveform Autor Transformer Starting from Protection Relay

Table 1. *Matrix Comparison between Autransformer, VVCF and VVVF Method*

Parameter	Method of Soft Starting		
	Auto Transformer	**Variable Voltage Constant Frequency (VVCF)**	**Variable Voltage Variable Frequency (VVVF)**
Voltage Transition	Step Voltage	Ramp	Ramp
Transition Time	17 second	17 second	17 second
Customize Voltage Starting	Impossible	Possible	Possible
Allowed Minimum Voltage	90% Vnominal	60% Vnominal	0% Vnominal
Frequency Transition	Constant Frequency	Constant Frequency	Ramp
Volt per Hertz (v/f) ratio	Reduced	Greatly Reduced	Constant
Air Gap Magnetic Flux Weakening	Yes	Yes	Only at Low frequency (< 10% fnominal) due to resistive stator drop voltage
Accelerating Torque Output	Reduced - Approx 80% at start	Reduced - Approx 36% at start	Approx Constant Torque Characteristic
Stall Critical Voltage	unknown	below 60% Vnominal	almost nothing
Peak Starting Current	4 times rms FLA	3 times rms FLA	Below rms FLA
Root Mean Square Current for 17s Ramp	Greater than 470 A	Greater than 470 A	Below 470 A
I2*t characteristic within 17s accelerating time (Rotor Thermal Dissipation)	Greater than rotor heating limit Approx. 377.43%	Greater than rotor heating limit Approx 392.72%	Lower than rotor heating limit Approx only 26.86%
Consecutive Starting	Max 4 times higher may cause heat stress	Max 3 times higher may cause heat stress	Unlimited , heat stress can be avoided due to lower heating limit
Reactive Power Response during Starting	High X/R ratio characteristic	High X/R ratio Characteristic	Low X/R ratio Characteristic
Highest Starting Reactive Power (VAR)	6.3 times greater than Full Load VAR	5.3 times greater than Full Load VAR	at rated Full Load VAR
Voltage Stability during Starting	Unstable	Unstable	Very Stable
Mechanical Power Raise Up	High Gradient	High Gradient	Controllable to Generator Governor Response
Frequency Stability	May Lead to Underfrequency Trigger	Still May Lead to Underfrequency Trigger	Very Stable
Pose Risk of Switching Surge	Very High Risk	No Switching Surge Phenomena	No Switching Surge Phenomena

starting current to below FLA, greatly reduces rotor heating, and eliminates switching surges. Voltage and frequency remain stable, and mechanical power rise is compatible with generator governor response, improving overall grid stability.

Adoption of VSD technology is therefore recommended as the preferred advanced motor starting technique for high-power high-frequent starting industrial applications in refinery environments.

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BEYOND CARBON CAPTURE AND FLARE REDUCTION: **THE ECONOMIC AND TECHNICAL FEASIBILITY OF METHANATION IN INDONESIA'S ENERGY TRANSITION**

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ABSTRACT

The oil and gas industry is responsible for significant carbon and methane emissions, contributing to climate change and energy security challenges. With methane emissions from ASEAN's oil and gas sector reaching 0.32 million tonnes in 2023, equivalent to 9 million tonnes of CO_2, urgent action is required. This paper introduces CO_2 methanation with green hydrogen as a transformational solution to decarbonize the industry while maintaining operational sustainability.

Methanation technology offers a threefold advantage: (1) reducing CO_2 emissions by capturing and converting them into synthetic methane (e-methane), (2) enhancing renewable energy efficiency by storing surplus electricity as green hydrogen, and (3) strengthening energy security by producing a sustainable substitute for depleting natural gas reserves. By utilizing the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$), captured carbon can be converted into synthetic natural gas, seamlessly integrating with Indonesia's existing LNG and natural gas infrastructure.

Drawing insights from Japan's advanced methanation projects, this paper explores the technical feasibility, economic viability, and scalability of implementing this technology within Indonesia's oil and gas operations. It highlights cost-benefit analyses, policy recommendations, and pathways for industry adoption. Given Indonesia's commitment to methane reduction and energy transition, methanation stands as a critical enabler of a carbon-neutral oil and gas sector, providing both environmental and economic benefits. This paper aims to encourage Indonesian energy stakeholders to consider methanation as a viable decarbonization strategy for long-term sustainability.

1. INTRODUCTION

1.1 Decarbonization and Energy Security in Indonesia's Oil & Gas Sector

Indonesia's oil and gas industry is a cornerstone of the nation's economy but also a significant contributor to greenhouse gas (GHG) emissions, particularly from surface facilities, where CO_2 and methane are routinely vented, flared, or lost in processing inefficiencies. In 2023, Indonesia's oil and gas methane emissions reached 0.32 million tonnes, equivalent to 9 million tonnes of CO[1]as seen in Figure 1.

Methane emissions have 84 times the global warming potential (GWP) of CO_2 over a 20-year period, making their mitigation a high-impact strategy for both climate action and resource recovery [1].

Furthermore, unutilized methane from flaring and venting represents an estimated 0.5 billion cubic meters of natural gas lost annually, translating into $87 million in revenue loss [1]. Simultaneously, Indonesia's natural gas production has been declining at a rate of 3.2% per

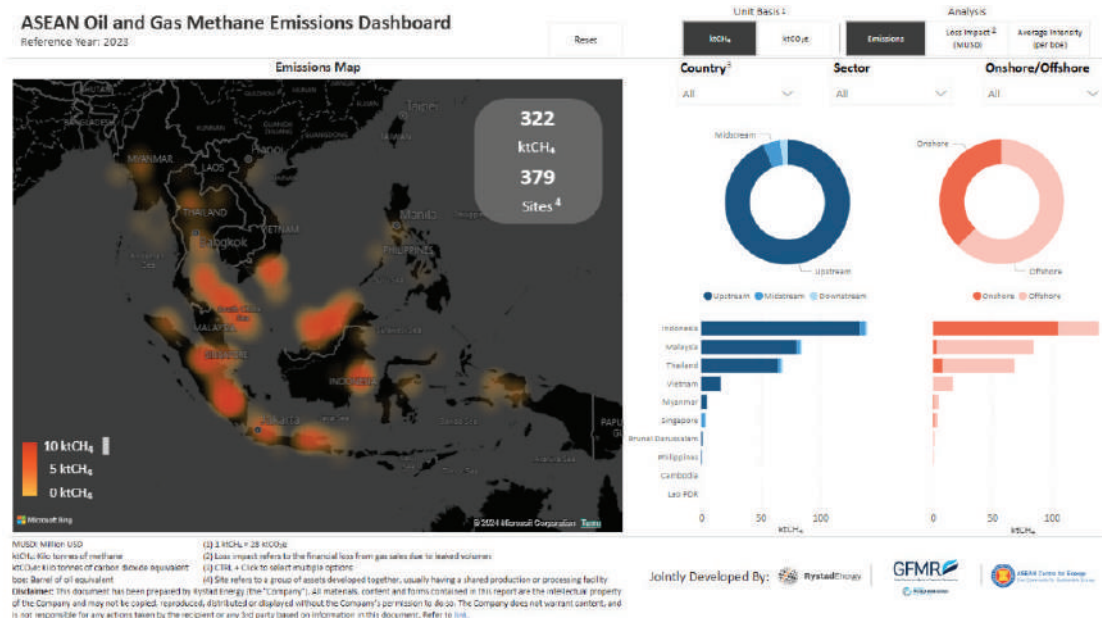


Figure 1. ASEAN MAESTRO Dashboard

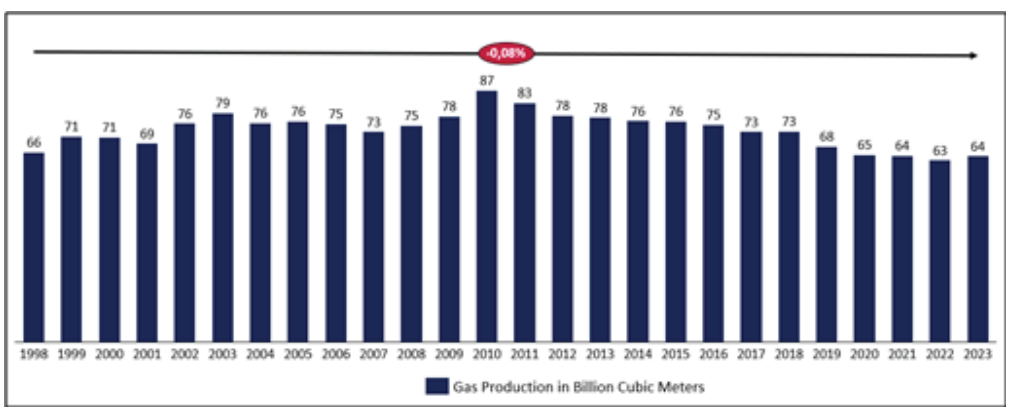


Figure 2. Gas Production Indonesia 1998-2023, cumulative decrease of 0.08%

year as seen on Figure 2, raising concerns about energy security and long-term sustainability [2]

1.2 Methanation as a Surface Facility-Based Decarbonization Strategy

To address these dual challenges, methanation technology, reacting captured CO_2 with green hydrogen production to produce synthetic methane, presents a scalable, surface facility-integrated approach to reducing emissions while recovering lost hydrocarbons. By capturing CO_2 from surface facility operations and reacting it with H_2 via the Sabatier reaction, the process yields synthetic methane (CH_4), which can be used as a drop-in replacement for fossil natural gas. The simplified process can be seen on Figure 3.

This technology is particularly relevant for Indonesia's oil and gas surface facilities, as it enables:

- On-site CO_2 utilization, reducing emissions from gas processing plants, refineries, and LNG terminals.
- Circular methane recovery, mitigating methane slip from flaring and venting operations.
- Integration with LNG infrastructure, allowing synthetic methane to be liquefied, stored, or transported through existing gas pipelines [2]

1.3 Industrial Feasibility of CO_2 Methanation in Indonesia

Indonesia is well-positioned to integrate CO_2 methanation within its existing surface facility networks, thanks to:

- Established CCUS projects that provide high-purity CO_2 for methanation [3].
- Large-scale LNG and pipeline infrastructure that can accommodate synthetic methane without major modifications [3].
- Competitive hydrogen production potential, leveraging solar, hydro, and geothermal energy resources to drive green hydrogen electrolysis.

With global synthetic methane prices expected to reach parity with LNG by 2035, CO_2 methanation represents a cost-effective, technically viable, and environmentally sustainable solution for

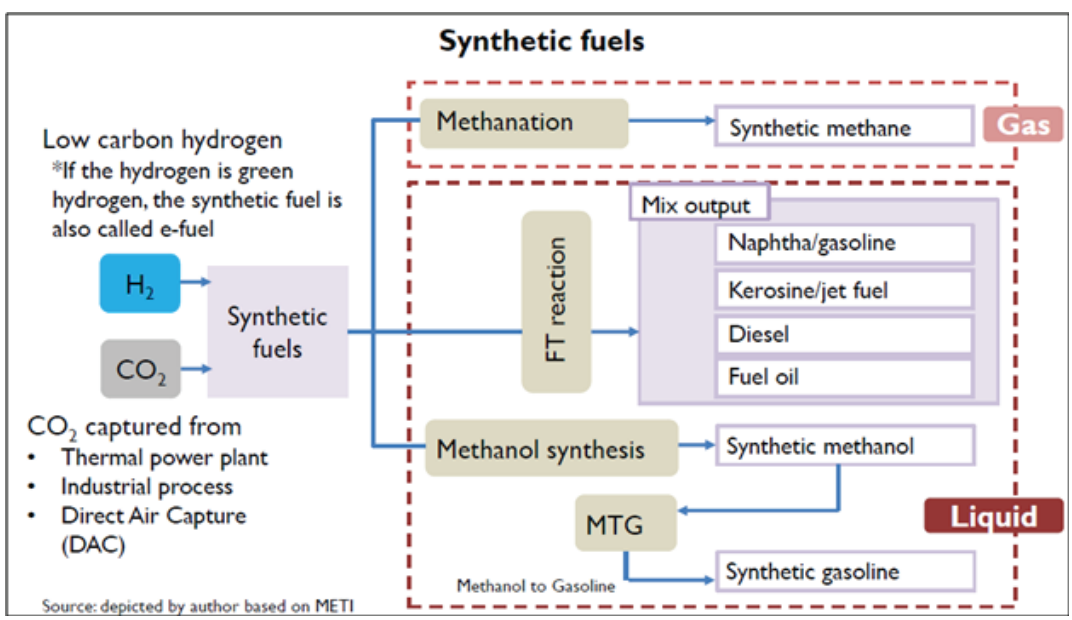


Figure 3. Synthetic methane (e-methane) process flow

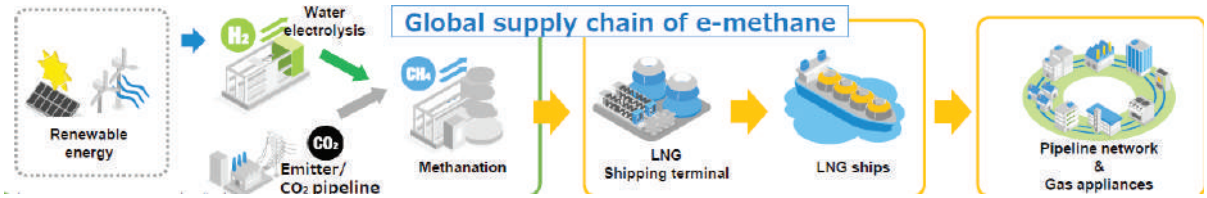


Figure 4. e-Methane Global Supply Chain

Indonesia's oil and gas sector [3]. Figure 4 shows the global supply chain of synthetic methane where Indonesia can be involved in every step of the supply chain.

2. The Science Behind Methanation: Process Engineering for Surface Facilities

precise thermal management to prevent catalyst degradation. Given the presence of CO_2-rich waste streams in surface facilities, including gas processing plants, LNG terminals, and refineries, methanation presents a viable pathway for emissions reduction and synthetic methane production [3] The integration of methanation

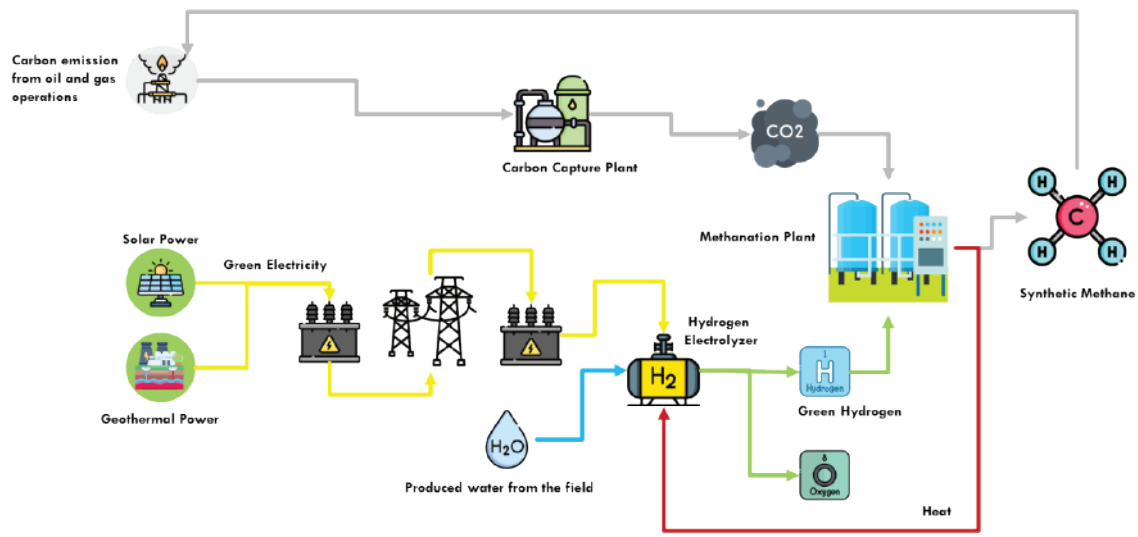


Figure 5. Simplified process flow diagram for combined CCS – Hydrogen for integrated methanation process in oil and gas surface facilities

2.1 The Sabatier Reaction: Industrial Application in Surface Facilities

CO_2 methanation, based on the Sabatier reaction, is a catalytic hydrogenation process that converts carbon dioxide (CO_2) and hydrogen (H_2) into methane (CH_4) and water (H_2O):

The reaction, operating at 300–500°C and 1–30 bar, is highly exothermic, necessitating

process with existing surface facilities can be seen on Figure 5.

2.2 Process Optimization: Catalysts and Reaction Conditions

The efficiency of CO_2 methanation is contingent on catalyst selection, reactor design, and process control. The reaction is thermodynamically favorable at lower temperatures, but kinetically hindered, necessitating catalyst optimization.

Table 1. Industrial Methanation Process Conditions

Parameter	Optimal Range	Impact on Reaction
Temperature	300–500°C	Enhances reaction kinetics but accelerates catalyst sintering.
Pressure	1–30 bar	Higher pressure favors CH_4 selectivity but increases operational costs.
Catalysts	Nickel (Ni) or Platinum (Pt)-based	Determines reaction rate, selectivity, and deactivation resistance.
H_2:CO_2 Ratio	4:1 molar ratio	Ensures complete CO_2 conversion, prevents CO formation.

The key process parameters are summarized in Table 1.

In surface facility applications, Ni-based catalysts are preferred due to their cost-effectiveness and high CH_4 selectivity, whereas Pt-group metals (Pt, Ru) offer superior coking resistance for high-CO_2 flue gas streams[3]

Table 2. Industrial Reactor Technologies for Methanation

Reactor Type	Key Advantages	Application
Fixed-Bed Reactor	High conversion efficiency, robust operation	Large-scale CO_2 methanation in refineries and LNG terminals
Fluidized-Bed Reactor	Superior heat management, reduced catalyst deactivation	Dynamic CO_2 feed conditions (e.g., CCUS-integrated facilities)
Microchannel Reactor	Compact design, rapid thermal dissipation	Modular or decentralized methanation applications

2.3 Reactor Engineering: Large-Scale Deployment Considerations

Integration of methanation within oil and gas surface facilities necessitates reactor designs that accommodate variable CO_2 flow rates, thermal loads, and catalyst deactivation risks. Table 2 outlines key reactor configurations.

2.3.1 Thermal Control and Energy Integration

The Sabatier reaction generates substantial heat, which, if not managed properly, leads to hot spots, catalyst deactivation, and reactor inefficiencies. Industrial methanation systems employ:

- Internal heat exchangers to improve thermal uniformity.
- Recirculating gas flows to optimize temperature distribution.
- Waste heat recovery for hydrogen catalyzer processes through hybrid Sabatier process (Figure 6), enhancing overall energy efficiency[3]

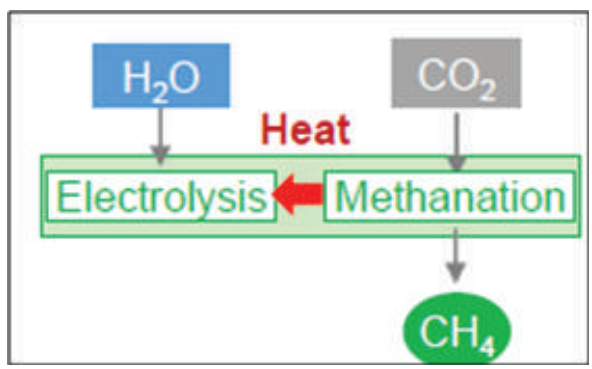


Figure 6. Hybrid Sabatier Process

2.4 CO_2 Sourcing: Integration with Surface Facility Emission Streams

Successful methanation implementation depends on a consistent, high-purity CO_2 supply,

Table 3. *CO_2 Capture Methods for Methanation Integration*

CAPTURE METHOD	PRIMARY SOURCE	ADVANTAGES	CHALLENGES
Post-Combustion Capture	Flue gas (power plants, refineries)	High readiness level	High energy requirement for solvent regeneration
Pre-Combustion Capture	Gasification, hydrogen production	High CO_2 purity	Requires additional infrastructure
Direct Air Capture (DAC)	Atmospheric CO_2	Independent of industrial sources	Energy-intensive, high CAPEX

typically sourced from gas processing units, LNG facilities, and refinery hydrogen plants. Table 3 categorizes CO_2 capture methodologies.

For Indonesia's surface facilities, post-combustion capture from refinery flue gas and pre-combustion CO_2 from amine sweetening units are the most feasible options[3].

2.5 Produced Water as an Electrolysis Feedstock for Hydrogen Production

Water scarcity is a critical constraint for green hydrogen production. Produced water from oilfields presents a potential alternative feedstock, though it requires advanced treatment due to:

- High salinity, necessitating desalination (reverse osmosis, electrodialysis).
- Organic contaminants, requiring oxidation or membrane filtration.
- Heavy metals, which degrade electrolyzer membranes[2]

2.5.1 Process Considerations for Surface Facility Adaptation

Integrating produced water electrolysis within oil and gas facilities allows:

- On-site hydrogen production, eliminating transportation costs.
- Closed-loop water management, reducing environmental discharge.
- Lower operational costs through wastewater valorization[3]

3. The Threefold Benefit of Methanation in Oil & Gas Surface Facilities

3.1 CO_2 Emission Reduction and Carbon Management

CO_2 emissions from surface facilities remain a critical challenge in Indonesia's oil and gas sector, particularly in gas processing plants, LNG terminals, and refineries. Flaring, venting, and inefficient gas treatment result in substantial CO_2 and methane emissions, contributing to climate concerns and operational inefficiencies. In 2023, Indonesia's methane emissions from oil and gas operations reached 0.32 million tonnes, equivalent to 9 million tonnes of CO_2[1].

Methanation technology directly addresses

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \; ; \; \Delta H = -165 \frac{kJ}{mol}$$

this issue by capturing CO_2 emissions at the source and converting them into synthetic methane (CH_4) via the Sabatier reaction:

This approach is particularly well-suited for refineries, natural gas processing plants, and CCUS-equipped facilities, where concentrated CO_2 streams are readily available[3]. The integration of methanation enables the direct utilization of captured CO_2, reducing emissions while producing a commercially viable fuel.

3.1.1 Mitigating Methane Emissions and

Enhancing Gas Utilization

Methane emissions from flaring and venting operations represent both an environmental and economic loss. Methanation provides an alternative pathway by enabling methane recovery and conversion into synthetic natural gas (SNG). Figure 5 captures the simplified process flow diagram design for these opportunities:

- **Flaring Reduction**: Capturing associated gas and converting its CO_2 content into methane improves overall hydrocarbon utilization.
- **Refinery Hydrogen Plant Synergies**: Refinery hydrogen production emits CO_2 as a byproduct. Methanation can repurpose this CO_2 to produce additional methane for fuel blending or grid injection[3].
- **CCUS Integration**: Methanation aligns with CCUS strategies by providing an alternative to CO_2 sequestration, effectively closing the carbon cycle within surface facilities.

methane offers long-duration storage using existing gas infrastructure. The process follows three distinct steps:

1. **Electrolysis**: Excess solar, wind, or geothermal power is used to generate green hydrogen from water.
2. **Methanation**: Captured CO_2 reacts with hydrogen to form synthetic methane, a storable fuel.
3. **Grid Injection**: The methane is injected into existing LNG terminals, CNG networks, and gas pipelines, eliminating the need for dedicated hydrogen infrastructure[3].

3.2.2 Comparative Analysis: Hydrogen vs. Synthetic Methane for Energy Storage

By converting hydrogen into synthetic methane, the P2G system enables long-term, grid-scale renewable energy storage, ensuring stability without requiring large-scale infrastructure changes[3]

Table 4. Comparative Analysis of Energy Storage

PARAMETER	HYDROGEN (H_2)	SYNTHETIC METHANE (CH_4)
Storage Infrastructure	Requires high-pressure tanks or cryogenic liquefaction	Uses existing LNG and gas infrastructure
Energy Density	33.6 kWh/kg	50.0 kWh/kg (higher than H_2)
Transport Feasibility	Requires dedicated pipelines	Compatible with LNG, CNG, and existing gas networks

3.2 Enhancing Renewable Energy Storage and Grid Stability

Indonesia's renewable energy sector faces a key limitation: the variability of solar and wind power requires effective energy storage solutions. CO_2 methanation enables a power-to-gas (P2G) system, where excess renewable energy is stored as synthetic methane.

3.2.1 Methanation as a Chemical Energy Storage Solution

Unlike batteries, which have limited energy density and degradation issues, synthetic

3.3 Strengthening Energy Security and Reducing LNG Dependency

Indonesia's natural gas reserves are projected to decline by 3.2% annually, while domestic gas demand is expected to rise by 60% by 2050[2]. Methanation offers a strategic pathway to supplement declining natural gas production, reducing reliance on imported LNG.

3.3.1 Synthetic Methane as a Direct Replacement for Fossil Natural Gas

- **Drop-in compatibility with existing**

infrastructure: Indonesia's LNG terminals, gas pipelines, and power plants can utilize synthetic methane without modifications.

- **Enhancing gas supply flexibility**: Methanation allows for on-demand methane production, improving gas network resilience.
- **Export opportunities**: Japan and the EU have set targets for synthetic methane imports, creating new market potential for Indonesia's gas sector[3].

3.3.2 Economic Viability and Cost Competitiveness

FACTOR	ECONOMIC IMPACT
Recovered methane emissions	$87 million/year in lost gas value[1]
Carbon pricing & credits	Potential $45 billion global revenue by 2030[1]
Synthetic methane cost parity with LNG	Expected by 2035[3]

4. Technological Integration of Methanation into Oil & Gas Surface Facilities

4.1 Industrial Deployment of Methanation in Oil & Gas Operations

Methanation technology has progressed from conceptual feasibility to industrial applicability, making it a viable decarbonization pathway for oil and gas surface facilities, particularly within gas processing plants, LNG terminals, and refineries. The successful implementation of methanation requires seamless integration with existing infrastructure to ensure operational efficiency, economic viability, and regulatory compliance.

Key components required for full-scale deployment include:

- CO_2 capture and purification systems to supply high-purity feedstock.
- Hydrogen generation units, leveraging electrolysis or steam methane reforming (SMR) with CCUS.
- Catalytic methanation reactors, optimized for continuous operation under industrial conditions.
- Gas treatment and compression systems to align with pipeline and LNG specifications.

In Indonesia, the growing deployment of carbon capture, utilization, and storage (CCUS) provides a strategic foundation for methanation. By diverting captured CO_2 into synthetic methane production rather than long-term sequestration, surface facilities can create an additional revenue stream while achieving net-zero emissions targets[3].

4.2 CO_2 Capture and Processing for Methanation

4.2.1 CO_2 Feedstock and Capture Technologies

The efficiency of a methanation system depends on the availability of a consistent, high-purity CO_2 stream. In surface facilities, CO_2 can be sourced from:

- Amine-based gas sweetening units in natural gas processing plants.
- Post-combustion CO_2 capture from refinery boilers and furnaces.
- CO_2 vent streams from hydrogen production units.
- High-purity CO_2 from LNG liquefaction and CCUS projects.

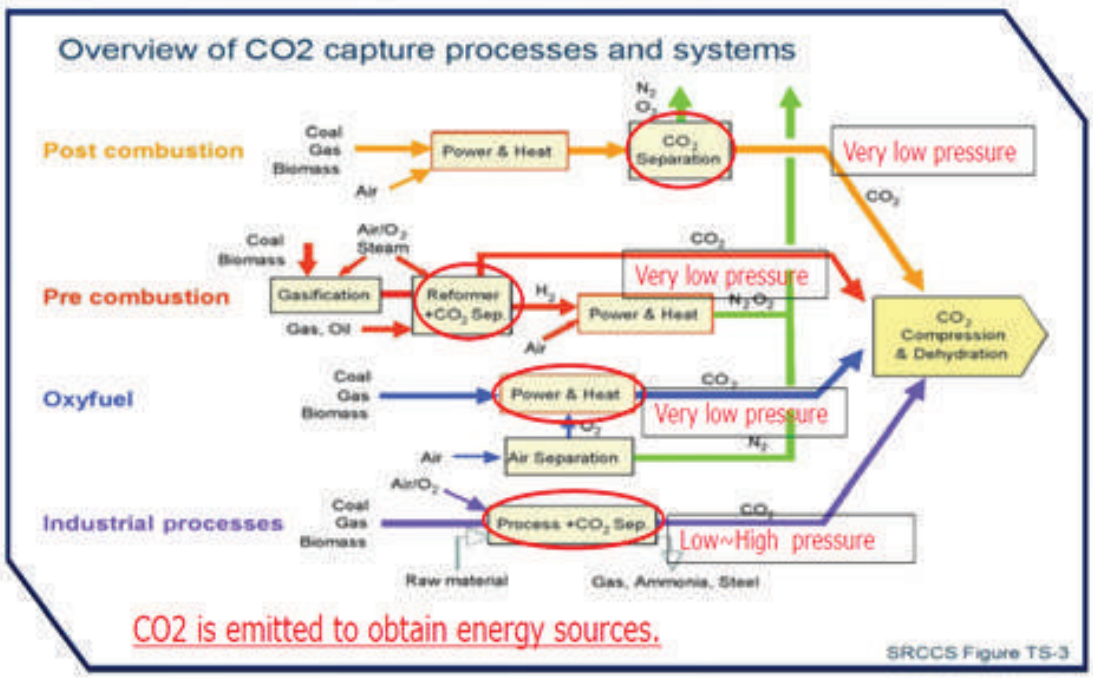


Figure 7 .Overview of Carbon Capture Processes and Systems

The economic feasibility of methanation is optimized when CO_2 is captured at high concentrations (>95% purity), reducing the need for extensive gas separation and purification[3] Figure 7 shows the process for carbon capture.

4.2.2 CO_2 Compression and Conditioning

For direct use in methanation reactors, CO_2 must meet strict purity, pressure, and moisture specifications. The conditioning requirements are outlined in Table 1.

Table 1. CO_2 Conditioning Standards for Methanation Reactors

PARAMETER	INDUSTRY STANDARD	IMPACT ON PROCESS
CO_2 Purity	>95%	Minimizes catalyst deactivation and side reactions.
Moisture Content	<100 ppm	Prevents reactor fouling and corrosion.
Compression	3–6 MPa	Ensures stable flow into reactor systems.

4.3 Hydrogen Supply and Electrolysis Integration

The economic and environmental performance of methanation is contingent on hydrogen supply reliability and cost competitiveness. Figure 8 shows the whole hydrogen value and supply chain. Key hydrogen production routes include:

- Electrolysis (Green Hydrogen): Powered by renewable energy sources, ensuring zero-carbon operation.
- SMR with CCUS (Blue Hydrogen): Utilizing methane as a feedstock while capturing CO_2 emissions.
- Methane Pyrolysis (Turquoise Hydrogen): Producing solid carbon as a byproduct,

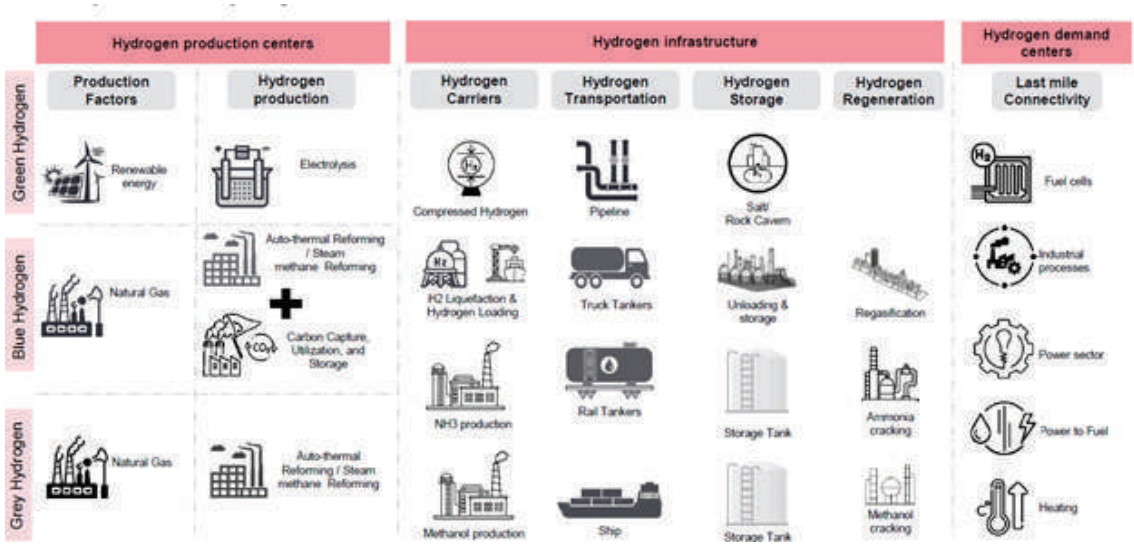


Figure 8. *Hydrogen Value and Supply Chain*

eliminating CO_2 emissions.

4.4 Integration of Synthetic Methane into Gas and LNG Infrastructure

4.4.1 Grid and LNG Compatibility of Synthetic Methane

Unlike hydrogen, which requires dedicated infrastructure, synthetic methane (SNG) is chemically identical to natural gas, allowing direct integration with Indonesia's:

- Gas transmission and distribution networks.
- LNG liquefaction and regasification terminals.
- Gas-fired power plants and industrial consumers.

4.5.2 Modifications Required for LNG Facility Integration

LNG terminals can be adapted for synthetic methane production by:

- Adjusting cryogenic storage conditions for CH_4 blends.
- Implementing gas quality control to meet pipeline specifications.
- Integrating methanation with boil-off gas recovery systems.[3]

5. Economic and Policy Feasibility of Methanation in Indonesia's Oil & Gas Industry

5.1 Economic Viability of Industrial-Scale Methanation

The commercial viability of CO_2 methanation in Indonesia's oil and gas sector is contingent on its ability to achieve cost competitiveness with conventional natural gas and LNG imports. The primary economic determinants include:

- Hydrogen production costs, which constitute 50–70% of total methanation expenses.
- CO_2 capture and conditioning costs, influenced by feedstock purity and processing efficiency.
- Capital expenditure (CAPEX) for reactor deployment and integration with existing infrastructure.
- Regulatory incentives, including carbon pricing and emission reduction policies.

A comparative cost analysis of synthetic methane (SNG) versus conventional natural

Table 1. Cost Comparison: Synthetic Methane vs. Natural Gas

PARAMETER	SYNTHETIC METHANE (SNG)	NATURAL GAS (LNG/ PIPELINE)
Production Cost ($/MMBtu)	8–15	6–10
Carbon Intensity (kg CO_2/MMBtu)	~0 (net-zero with CCUS)	~56 (conventional LNG)
Infrastructure Requirement	Compatible with existing gas networks	Established infrastructure
Market Maturity	Emerging	Fully developed

gas is presented in Table 1.

Although SNG production costs remain above fossil gas, declining hydrogen prices and expanding carbon markets are expected to drive cost parity by 2035, enhancing the financial case for large-scale deployment[3]

5.2 Hydrogen Cost Dynamics and Impact on Methanation Economics

Hydrogen procurement represents the most significant cost variable in methanation operations. The Levelized Cost of Hydrogen (LCOH) is dependent on production technology,

Table 2. Hydrogen Production Costs for Methanation ($/kg H_2)

PRODUCTION METHOD	CURRENT COST (2024)	PROJECTED COST (2035)
Green Hydrogen (Electrolysis)	4.5–6.0	1.5–3.0
Blue Hydrogen (SMR + CCUS)	1.5–2.5	1.0–1.8
Turquoise Hydrogen (Methane Pyrolysis)	2.0–3.5	1.2–2.2

as outlined in Table 2.

The cost reduction trajectory of green hydrogen is driven by advancements in electrolyzer efficiency, economies of scale, and declining renewable energy prices. By 2035, electrolysis-based hydrogen is expected to approach cost parity with blue hydrogen, thereby improving the economic competitiveness of methanation[2].

5.3 Carbon Pricing and Policy Incentives

5.3.1 Carbon Market Mechanisms in Indonesia

Indonesia has introduced carbon pricing instruments aimed at accelerating the transition to low-carbon fuels, including:

- Carbon tax implementation ($2/t$CO_2$ in 2025, with planned escalations).
- Emission trading schemes (ETS) for industrial sectors.
- CCUS incentives for industries utilizing captured CO_2 in value-added applications.

With global carbon prices projected to exceed $75/t$CO_2$ by 2030, the cost competitiveness of synthetic methane relative to conventional LNG will improve, enhancing its commercial viability[1]

5.3.2 Global Policy Benchmarks for Synthetic Methane Adoption

Several jurisdictions have implemented regulatory frameworks to accelerate methanation deployment, including:

- Feed-in tariffs for synthetic fuels (Japan, Germany).
- Tax incentives for low-carbon hydrogen and

CCUS projects (USA, EU).
- Renewable gas blending mandates (France, South Korea).

Indonesia's policy landscape must evolve to provide similar mechanisms, particularly within LNG supply chains and gas-fired power generation, to establish a competitive synthetic methane market[3]

5.4 Investment Requirements and Industrial Implementation

5.4.1 Capital Expenditure (CAPEX) Analysis

A full-scale 50 MW methanation facility entails a capital investment ranging from $250–350 million, with cost allocation detailed in Table 3.

Table 3. CAPEX Breakdown for Methanation Deployment ($ million)

COMPONENT	ESTIMATED COST
CO_2 Capture & Purification	60–80
Electrolysis & Hydrogen Supply	100–150
Methanation Reactor & Processing	50–70
Infrastructure & Grid Integration	40–50

The operational cost structure is largely dictated by electricity tariffs for hydrogen production and CO_2 feedstock acquisition, necessitating preferential power tariffs and policy-backed subsidies to enhance investment attractiveness[3]

5.4.2 Industrial Deployment Strategy

A phased approach is recommended for methanation adoption in Indonesia's energy sector:

1. Pilot-Scale Demonstrations (2024–2028): Small-scale methanation plants co-located with CCUS sites.
2. Industrial Integration (2028–2035): Large-scale deployment in gas processing plants, refineries, and LNG terminals.
3. Full Market Adoption (2035 onward): Synthetic methane as a standardized fuel within Indonesia's domestic gas and LNG supply chains.

6. Lessons from Global Methanation Projects: Implications for Indonesia

6.1 Overview of Global Methanation Deployments

Several countries have pioneered CO_2 methanation projects to advance low-carbon fuel production, carbon utilization, and power-to-gas (P2G) strategies. Key case studies from Germany, Japan, Denmark, and France provide critical insights into technical performance, economic feasibility, and regulatory support.

Table 1 summarizes major international

Table 1. Major International Methanation Projects

PROJECT	COUNTRY	CAPACITY (MW)	CO_2 SOURCE	HYDROGEN SOURCE	END-USE APPLICATION
Audi e-gas	Germany	6	Biogas	Electrolysis	Grid Injection
STORE&GO	Europe (Multi)	1.2	Industrial CO_2	Wind-Powered Electrolysis	Power-to-Gas (P2G)
Fukushima Hydrogen Energy Research	Japan	10	Industrial CCUS	Solar-Powered Electrolysis	Hydrogen & Methane Production
Electrochaea Biocatalysis Plant	Denmark	1	Biogenic CO_2	Electrolysis	Grid Injection & Industry
Jupiter 1000	France	1	Industrial CO_2	Wind & Solar Electrolysis	Grid Injection & LNG

methanation projects, highlighting technology readiness, capacity, and integration with existing infrastructure.

The operational performance of these projects demonstrates the scalability and integration potential of methanation, particularly in regions with high renewable energy penetration[3].

6.2 Key Lessons from Global Deployments

6.2.1 Technical Integration and Infrastructure Adaptation

- Methanation is fully compatible with existing gas infrastructure, reducing capital expenditure for new pipelines and storage facilities.
- CO_2 feedstock quality is a critical determinant of efficiency, requiring pre-treatment for contaminants such as sulfur and oxygen.
- Thermal management is essential, as reactor heat integration with district heating or industrial processes enhances system efficiency[3].

6.2.2 Economic and Market Feasibility

- Carbon pricing improves synthetic methane competitiveness, with projects in Germany and France benefiting from ETS (Emission Trading System) revenues.
- Hydrogen cost reduction is key, with Japan targeting a $1/kg hydrogen price by 2030 to enable cost-effective methanation.
- Investment in electrolyzer scaling lowers LCOH (Levelized Cost of Hydrogen), enhancing overall project economics[3].

6.2.3 Policy and Regulatory Frameworks

- Renewable gas blending mandates accelerate adoption, such as France's 10% synthetic methane injection target by 2030.
- Tax incentives for carbon utilization (Japan, USA) reduce project payback periods.
- Long-term power purchase agreements (PPAs) for hydrogen production stabilize energy costs, ensuring investment certainty[3].

6.3 Strategic Implications for Indonesia

6.3.1 Feasibility of Methanation in Indonesia's Oil & Gas Infrastructure

Given Indonesia's existing LNG terminals, gas pipelines, and CCUS initiatives, methanation presents a viable pathway for carbon-neutral gas production. Three key infrastructure adaptations are necessary:

- Integration with LNG facilities: Synthetic methane can be co-processed with conventional LNG, reducing overall carbon intensity.
- Use of amine sweetening CO_2 as a methanation feedstock: This aligns with Indonesia's existing gas processing operations.
- Hydrogen co-location at industrial hubs: Establishing methanation plants near refinery hydrogen production sites minimizes transport costs[3]

6.3.2 Investment Strategy and Policy Recommendations

- Introduce a Renewable Gas Standard (RGS) requiring synthetic methane blending in Indonesia's natural gas network.
- Leverage carbon pricing revenues to subsidize early-stage methanation projects.
- Develop hydrogen-methanation industrial

clusters to create economies of scale[2]

7. CONCLUSION AND RECOMMENDATIONS: A STRATEGIC ROADMAP FOR METHANATION DEPLOYMENT IN INDONESIA

7.1 Key Findings and Technical Insights

This study has demonstrated that CO_2 methanation is a technically viable and economically scalable solution for decarbonizing Indonesia's oil and gas sector. The integration of methanation within existing LNG terminals, gas processing plants, and refinery hydrogen production units presents a viable strategy for reducing emissions while enhancing energy security. The principal findings are summarized as follows:

- Technical Viability: Methanation technology is well-established, with proven industrial applications in Europe and Japan. It offers high CO_2 conversion efficiency, particularly when integrated with existing CCUS and hydrogen production infrastructure.
- Economic Potential: Cost projections indicate that synthetic methane will achieve cost parity with LNG by 2035, driven by declining hydrogen production costs and carbon pricing incentives.
- Infrastructure Synergy: Indonesia's extensive gas infrastructure, including its LNG export terminals and pipeline networks, enables direct integration of synthetic methane, reducing the need for additional capital investment.
- Policy Imperatives: Global case studies underscore the importance of carbon pricing, tax incentives, and renewable gas mandates in accelerating methanation adoption[2]

7.2 Strategic Recommendations for Large-Scale Deployment

7.2.1 Industrial and Infrastructure Integration

To facilitate the large-scale deployment of methanation in Indonesia, the following infrastructure adaptations are recommended:

- LNG Terminal Co-Processing: Methanation should be co-located with existing LNG regasification terminals to facilitate synthetic methane blending with conventional LNG streams, reducing overall carbon intensity.
- CO_2 Utilization from Gas Processing Plants: Amine sweetening units at gas processing facilities should be leveraged as primary CO_2 feedstock sources, reducing vented and flared emissions.
- Hydrogen Co-Location Strategy: Methanation facilities should be integrated with refinery hydrogen production units to minimize hydrogen transport costs and improve process efficiency[2]

7.2.2 Regulatory and Market Incentives

To create a favorable investment climate for synthetic methane production, the following policy mechanisms should be introduced:

- Renewable Gas Standards (RGS): Establish a regulatory framework requiring a minimum percentage of synthetic methane blending into Indonesia's natural gas network.
- Carbon Pricing Incentives: Expand emission trading schemes (ETS) and carbon taxation policies to enhance synthetic methane's cost competitiveness relative to fossil-based LNG.
- Investment Tax Credits & PPAs: Introduce financial incentives for industrial players investing in methanation, including tax reductions and long-term power purchase agreements (PPAs) for green hydrogen supply[3]

7.3 Roadmap for Methanation Implementation in Indonesia

A structured, phased approach is recommended for the successful adoption of methanation within Indonesia's oil and gas industry:

Phase 1 (2024–2028): Pilot Deployment & Feasibility Assessments

- Establish pilot-scale methanation plants integrated with CCUS facilities.
- Conduct techno-economic feasibility studies to refine business models and assess market viability.
- Secure government-backed incentives to support early-stage investment.

Phase 2 (2028–2035): Industrial-Scale Deployment

- Scale methanation integration at gas processing facilities, LNG terminals, and refinery hydrogen plants.
- Expand hydrogen production capacity to support high-volume methanation operations.
- Implement renewable gas mandates, requiring synthetic methane blending in domestic and export gas markets.

Phase 3 (2035 onward): Full Market Integration

- Establish synthetic methane as a standardized fuel for power generation, industrial feedstock, and LNG exports.
- Integrate methanation into national power-to-gas (P2G) strategies to enhance grid stability and renewables integration.
- Develop international partnerships to position Indonesia as a regional leader in synthetic methane production and trade[3].

7.4 Final Outlook: Positioning Indonesia as a Leader in Carbon-Neutral Gas

✓ Methanation offers a technically and economically feasible solution for Indonesia's oil and gas industry, enabling carbon-neutral operations and enhanced energy security.

✓ Declining hydrogen production costs and expanding CCUS initiatives will improve the economic competitiveness of synthetic methane relative to fossil LNG.

✓ A phased deployment strategy, backed by regulatory incentives and industrial investments, is necessary to scale methanation adoption.

✓ By integrating methanation into its national energy transition framework, Indonesia can establish itself as a key player in global synthetic methane markets

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He is currently the only Indonesian to hold a Certified Automation Cybersecurity Specialist from Exida, showing a strong competency in managing process safety risks related to cybersecurity. He has authored and presented more than fifteen technical papers at national and international conferences on project management, process safety, and digital technology deployment in the upstream oil and gas industry, which has recognized him as an industry expert and key opinion leader in the fields of data science, machine learning, artificial intelligence, and surface facilities engineering. He has also written a guidebook to starting a career in the oil and energy industry titled “Fueling Your Career”.

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TRANSFORMING ELECTRICAL SUBMERSIBLE PUMP OPERATIONS: **REAL-TIME DATA ACQUISITION AND MACHINE LEARNING FOR ENHANCED DIAGNOSTICS AND PRODUCTION OPTIMIZATION**

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ABSTRACT

Electrical Submersible Pump (ESP) is a widely used artificial lift method in the petroleum industry, requiring continuous monitoring to ensure optimal operation. Typically, sensor data from offshore fields takes 1-2 days to reach the main office, delaying the troubleshooting process and potentially prolonging production downtime. To overcome this problem, a real-time sensor data system was introduced, reducing data acquisition delays to approximately 5 minutes, enabling faster and more accurate ESP analysis. With real-time data, Machine Learning (ML) can be applied to improve ESP operations. A virtual production rate model is built using real-time sensor data, replacing costly and infrequent well tests. ESP health monitoring is enhanced through Principal Component Analysis (PCA) with Hotelling's T^2 statistics, providing a single value to assess pump conditions. Sensor trend analysis with moving averages further aids in troubleshooting by identifying sensor behaviour patterns and suggesting corrective actions. Additionally, when ESP failure occurs, real-time sensor parameters can be fed into a classification ML model to predict the failed component and its failure mechanism. This approach can reduce reliance on Dismantle, Inspection, and Failure Analysis (DIFA), a process that consumes extensive time and resources. The ML model development follows a systematic workflow, including data preprocessing, dimensionality reduction, model selection, and hyperparameter tuning to ensure reliable predictions. This real- time data and ML integration significantly reduces troubleshooting time, enhances failure diagnostics, and optimizes production through virtual flow rate estimation. The system provides a foundation for future ESP designs, with failure prediction accuracy improving as more real-time data becomes available. Ultimately, this approach has the potential to revolutionize ESP operations, minimizing downtime and lowering operational costs.

1. INTRODUCTION

Electrical Submersible Pumps (ESPs) have been one of the most utilized artificial lift methods in the petroleum industry for decades. Their widespread adoption, dating back to the 20th century, is primarily attributed to their high efficiency and reliability across a broad spectrum of well conditions compared to other artificial lift systems (Takacs, 2017). However, ESPs are susceptible to various failures, including mechanical and electrical issues, as well as operational problems. The likelihood of such failures increases significantly under harsh downhole conditions, such as high temperatures and pressures, the presence of sand in the produced fluids, and high gas content (Fakher et al., 2021).

Increased failure risk often leads to ESP trips, which can escalate to complete system failure. Improper ESP operation or suboptimal utilization can further result in heightened energy consumption, prolonged operational downtimes, and increased maintenance expenditures. Without effective troubleshooting protocols, diagnosing ESP trips can be time-consuming, directly contributing to extended Non-Productive Time (NPT). Furthermore, inadequate monitoring practices inevitably curtail the operational lifespan of these systems. Consequently, the implementation of robust troubleshooting and monitoring procedures is imperative for every ESP installation.

Such procedures, typically involving downhole monitoring systems that collect data from sensors, augmented by well test results and historical ESP performance data, have been standard practice at PHE OSES for several years. While these established methods offer a degree of reliability, certain areas present opportunities for enhancement. A notable challenge is the significant NPT incurred due to delays in data acquisition. Moreover, the

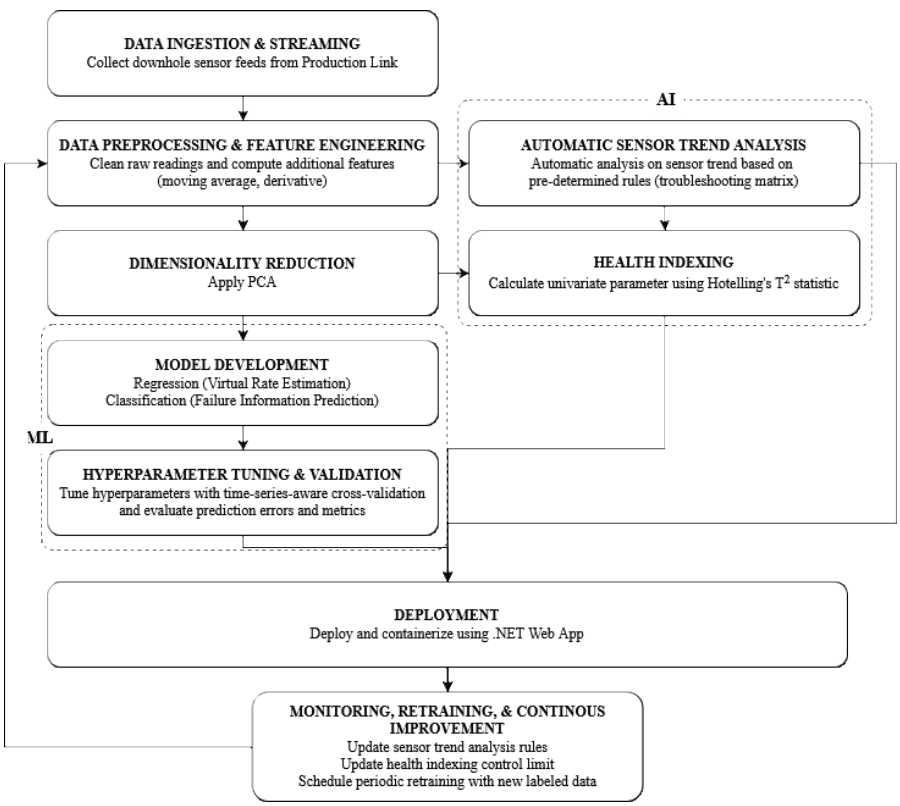


Figure 1. *End-to-end workflow*

absence of a comprehensive, end-to-end Machine Learning (ML) strategy—encompassing real-time monitoring, virtual production-rate modeling, fault classification, and predictive maintenance—restricts the capacity for truly proactive diagnostics and continuous performance optimization.

The introduction of Baker Hughes' ProductionLink downhole telemetry system has revolutionized data acquisition (El Gindy et al., 2025), enabling key ESP sensor data—including pressure, temperature, motor current, and vibration—to be transmitted to onshore analytics platforms in near real-time, typically within 1 to 5 minutes of collection. By drastically reducing the conventional data transfer latency from days to minutes, ProductionLink provides a continuous, high-resolution stream of pump operational data directly from the intake and discharge points. The availability of such structured, real-time data forms the bedrock for advanced machine learning workflows, thereby transforming ESP diagnostics into a proactive, data-driven endeavor as studied by Brasil et al (2022). The conceptual end-to-end workflow is illustrated in Figure 1.

2. METHODOLOGY

The ML workflow utilizes sensor measurements from multiple PHE OSES wells equipped with the ProductionLink monitoring system, along with historical well test data (e.g., Water Cut (WC), production rate, Gas Oil Ratio (GOR), etc.). The workflow commences with data ingestion and streaming, followed by data preprocessing, feature engineering, and dimensionality reduction. These processed data are then employed to develop several data-driven models. These include models for automatic sensor trend analysis, pump health monitoring (using Hotelling's T2 statistic), virtual production rate estimation, and failure information prediction.

2.1 Data Ingestion & Streaming

Downhole sensor measurements are streamed from a ProductionLink server to a SQL database at intervals ranging from one to five minutes. This data is organized into timestamped records for each sensor, facilitating efficient time-series querying. Subsequently, a database connection is established within a Python environment, where the ensuing steps of the workflow are executed.

2.2 Data Preprocessing & Feature Engineering

The workflow initiates with the systematic handling of missing or erroneous sensor readings. Missing values within the sensor data channels are addressed using Multivariate Imputation by Chained Equations (MICE). This technique iteratively models each variable as a function of theothers, rather than relying on simplistic approaches like mean imputation, allowing for more accurate and statistically valid estimates under the assumption of missing at random (MAR) conditions (van Buuren, 2018). Outliers are not removed and used as is because it is useful for the model to predict anomaly. Historical well test data undergo a similar preprocessing regimen with minor adjustments: features with over 70% missing values are excluded, outliers removal, and remaining missing values imputation using MICE.

Following data cleaning, feature engineering is performed by augmenting each sensor measurement with three derived metrics that capture trend behaviors. First, the finite-difference derivative is computed between adjacent timestamps to quantify the instantaneous rate of change. Second, a moving average, calculated over a fixed window, smooths short-term fluctuations and highlights underlying trends (Box, 2015). Third, a directional indicator based on changes in the moving average is encoded as +1 if the moving average is increasing, –1 if it is decreasing, and 0 if it remains effectively constant. These types of statistical and trend-based features have been

shown to effectively capture both short- and long-term dynamics in time- series data, enhancing the performance and interpretability of machine learning models (Fulcher & Jones, 2017). By appending these derivative, moving average, and directional features to the original sensor readings, the resultant dataset provides the ML models with inputs that reflect nuanced temporal patterns in ESP behavior.

2.3 Automatic Sensor Trend Analysis

A compilation of PHE OSES sensor trend combinations that characteristically precede or correlate with specific operational events is established through a systematic analysis of historical sensor data. This analysis covers both normal operational periods and instances of the target events. Utilizing techniques such as statistical analysis, data visualization, and domain expertise, trends of relevant sensors are identified. By leveraging these pre-defined characteristic profiles of sensor trend combinations, an automated sensor trend analysis module is developed. This module derives conclusions based on the observed trends from the sensors. The steps for the automatic sensor trend analysis are detailed as follows:

a. Baseline Calculation (Per Well)

From the latest 7 days of data, calculate mean, standard deviation, median, and Mean Absolute Deviation (MAD) (excluding NaNs and zero values). This defines the "normal" baseline.

b. Z-Score & Z-Med Score Calculation

Each new data point is transformed using z-score:

$$z = \frac{x - \mu}{\sigma} \qquad z_{med} = \frac{x - median}{MAD}$$

c. Trend Classification

The obtained z and z_{med} of each data point is mapped to different categories based on their value. Each of the categories is assigned a new value that will be used to calculate troubleshooting matrix matching score in the next step. The category mapping is given in Table 1.

Table 1. *Sensor trend category mapping.*

Z-Score Range*	Trend Category	Value
≤ −10	Sharp decrease	−3
−10 to −7	Decrease	−2
−7 to −3	Slight decrease	−1
−3 to +3	Stable	0
+3 to +5	Slight increase	+1
+7 to +10	Increase	+2
≥ +10	Sharp increase	+3

*based on available data characteristics.

d. Calculate Troubleshooting Matrix Matching Score

For each known failure type, a matrix called sensor trend characteristic profile exists, which are detailed in Figure 2. A metric named "Matching Score" is calculated as a parameter to observe the difference between observed trends and matrix trends which is given by:

$$Matching\ Score = 1 - \frac{\sum|observed\ category - matrix\ trend|}{number\ of\ parameters \times 6}$$

e. Failure Selection & Evaluation

For each z-score variation (i.e. z and z_{med}), flag any data range with score ≥ 0.80 as a candidate. Compare z vs z_{med} (e.g. using historical labels or alarm stability) to decide which to adopt or ensemble them.

f. Baseline Recalibration

Daily recompute mean, standard deviation, median, and MAD over the most recent days to adapt to drift.

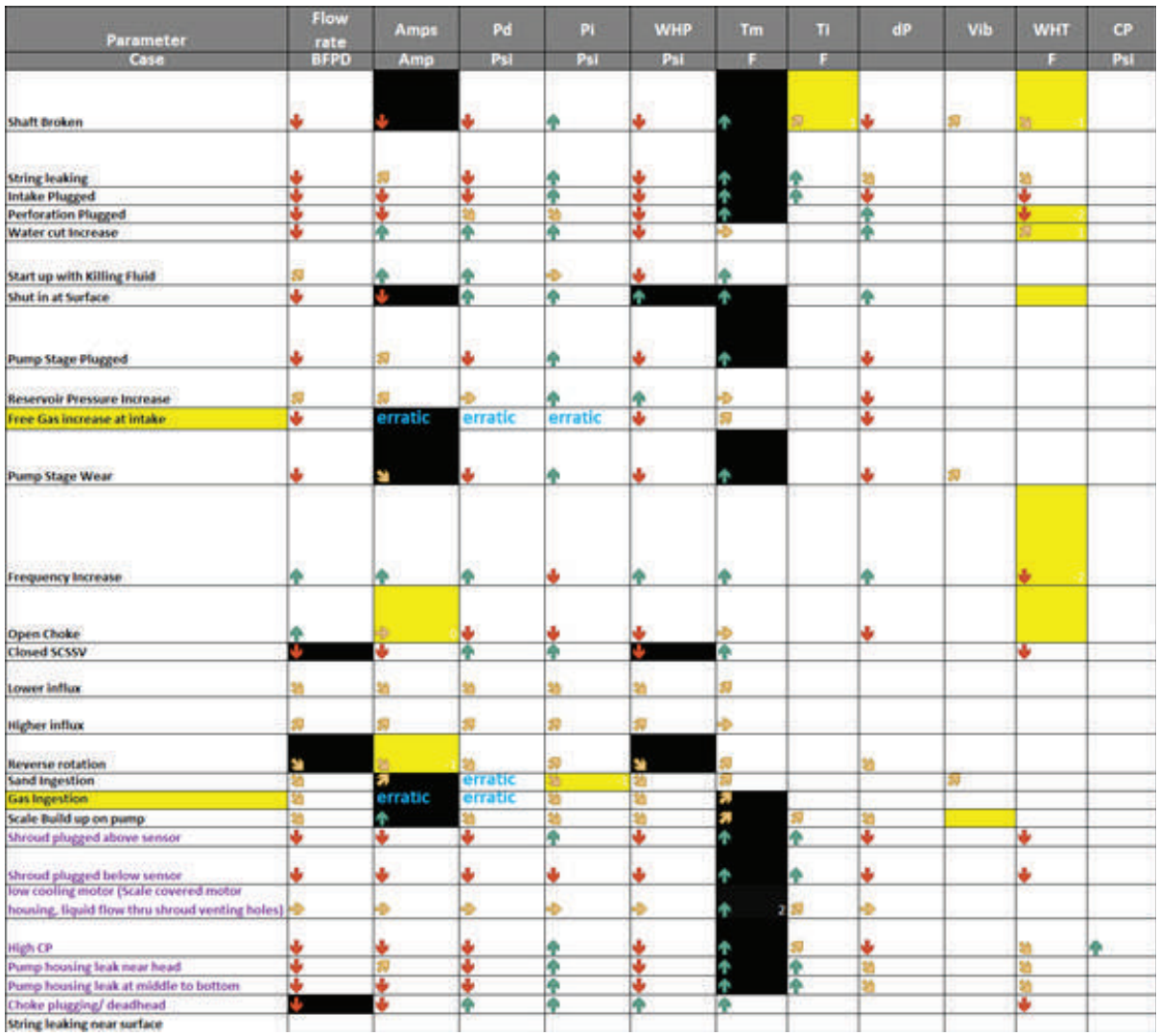


Figure 2. *Sensor trend characteristic profile.*

2.4 Dimensionality Reduction

Multicollinear variables, which can compromise the reliability and accuracy of ML models (particularly regression models) by inflating the variance of coefficient estimates and obscuring the individual importance of predictors, are identified using a combination of correlation matrices and the Variation Inflation Factor (VIF), a standard diagnostic metric for detecting multicollinearity (James et al., 2021). To mitigate multicollinearity, dimensionality reduction is applied to the identified set of multicollinear variables. This process reduces the number of features while endeavoring to minimize the loss of critical information. Principal Component Analysis (PCA) is the method employed for this dimensionality reduction (Jolliffe, 2021).

2.5 Pump Health Indexing

Subsequent to PCA, which isolates the dominant sources of variance in the multivariate sensor data, a Hotelling's T^2 statistic is computed to monitor pump health. This multivariate control metric quantifies the squared Mahalanobis distance of each observation from the PCA-modeled baseline, providing a single value that reflects how far a point deviates from the

established "normal" operating profile. In this study, rather than directly using p-values or assuming strict multivariate normality, we adopt a log-transformed Shewhart control approach (Montgomery, 2024) to define dynamic control limits for T^2-based anomaly detection. The overall process is detailed as follows:

a. Baseline Calculation (Per Well)

From the latest 7 days of data, calculate mean, standard deviation, median, and MAD (excluding NaNs and zero values). This defines the “normal” baseline.

b. Z-Score & Z-Med Score Calculation

Each new data point is transformed using z-score:

$$z = \frac{x - \mu}{\sigma} \qquad z_{med} = \frac{x - median}{MAD}$$

c. Iterative Filtering of Outliers

Mask any data points where both |z| and $|z_{med}|$ exceed a defined threshold (e.g., 3 or 5) as outliers and exclude them from the dataset. Recompute the mean, median, standard deviation, and MAD from the remaining data. Repeat the outlier detection and recalculation process iteratively until no further outliers are identified—indicating that the baseline statistics have stabilized and the dataset represents normal operating conditions.

d. PCA training

Fit a PCA model using only the filtered, fully normal data.

e. T^2 Calculation

Use the trained PCA model to compute Hotelling’s T^2 statistic for each observation.

f. T^2 Control Limit

To determine the Upper Control Limit (UCL), a log-Shewhart approach is used:

1) Log-transform the T^2 values.
2) Compute the mean and standard deviation
3) Define the control limit as: $UCL = \exp(\mu_{log} + z \cdot \sigma_{log})$

The control limits illustration is shown in Figure 3.

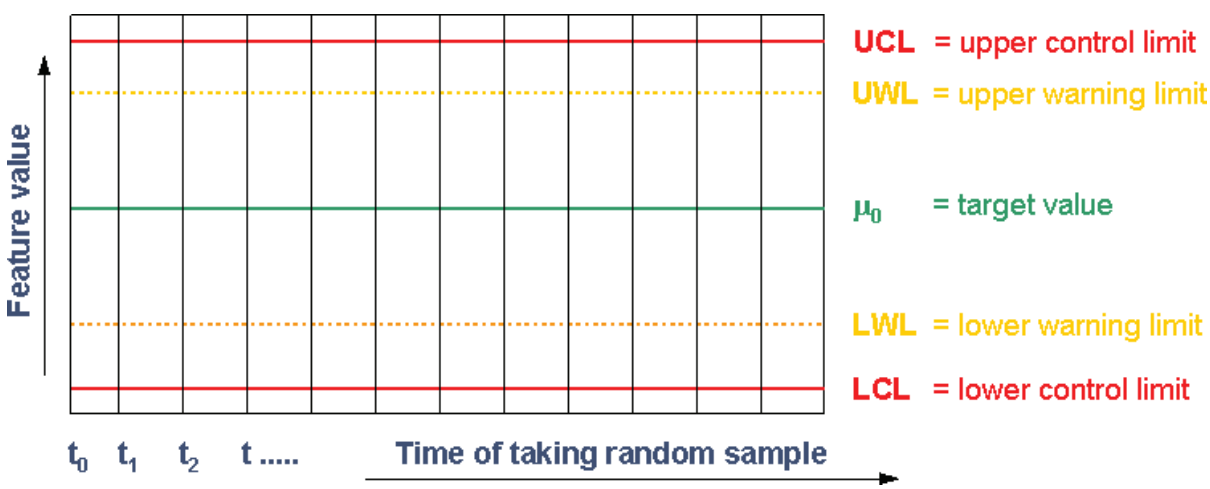


Figure 3. *Control limits illustration.*

g. Online Monitoring

For each new observed data point:

1) Scale using the latest normal baseline statistics.
2) Apply the trained PCA transformation.
3) Compute T^2.
4) Flag as anomalous if T^2 exceeds the control limit.

h. Weekly Baseline Statistics Update

Every week, repeat the first three steps using the most recent 7-day data to refresh the baseline statistics (mean, median, and standard deviation).

i. Monthly PCA Retraining

Retrain the PCA model monthly using the updated normal dataset.

2.6 ML Model Development

Two primary types of ML models are developed: regression models for virtual rate estimation and classification models for predicting failure information. The initial phase of model development involves data preparation, including specialized data splitting, normalization/standardization, model selection, and subsequent hyperparameter tuning.

a. Data Splitting

To mitigate data leakage and enhance model robustness, a specialized data splitting technique, adapted from the approach proposed by Andersen et al. (2022), is employed. The specific steps are detailed in Figure 4 and are as follows:

1) One well is entirely excluded from the dataset. This well, designated as unseen data, serves as a blind test set for the final model evaluation.
2) The remaining dataset is then divided into training and testing sets at an 80:20 ratio. This division adheres to time-series data splitting principles, where data is split chronologically. Specifically, for each of the remaining wells, the initial 80% of its chronological data constitutes the training set, while the subsequent 20% forms the testing set.

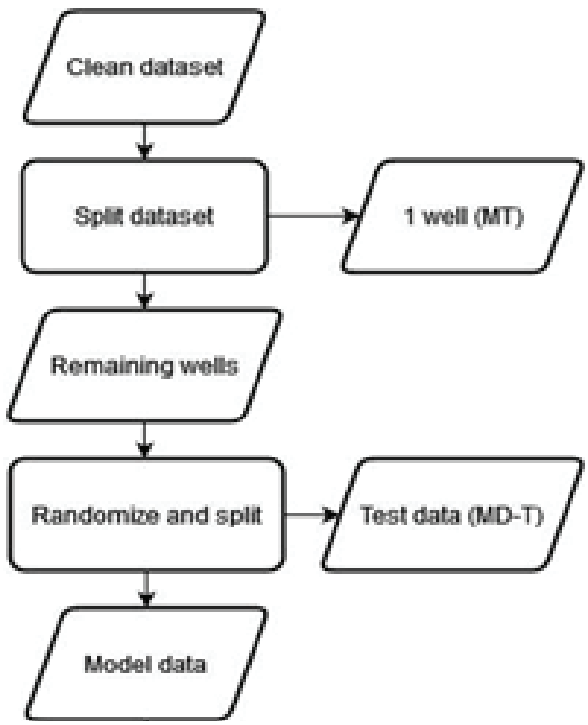


Figure 4. *Data splitting workflow.*

b. Data Normalization/Standardization

All data splits (training, testing, and unseen data) are standardized using the StandardScaler from scikit-learn before being used for model development. Standardization, which scales data to have zero mean and unit variance, is a common requirement for many ML algorithms. While StandardScaler is influenced by outliers, its application ensures that all features contribute more equally to model training (Ge´ron, 2022).

c. Model Selection

A variety of regression and classification algorithms are evaluated to identify the most suitable model for each task given the dataset characteristics. For regression models, a custom function is utilized to rank candidate models based on multiple performance metrics: Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Mean Absolute Error (MAE), and the p-value from a Kolmogorov-Smirnov (K-S) test applied to the model's residuals. The regression models are primarily ranked by RMSE, then by the K-S test p-value, followed by MAPE, and finally MAE. While the optimal ranking order can be task-dependent, prioritizing a K-S test p-value greater than 0.05 aims to select models whose residuals approximate a normal distribution, a desirable property for many regression applications.

Given the significant class imbalance observed within the failure classification dataset, model selection for this task is based on ranking each candidate model's F1-score. The F1- score is an appropriate metric for imbalanced datasets as it harmonically balances precision and recall. Once the optimal base classification model is identified, it is integrated into a hierarchical classification model wrapper. In a hierarchical system, the prediction tasks are organized in a tree-like structure, where each node represents a prediction task, and the edges represent dependencies between tasks (Silla & Freitas, 2011). This hierarchical structure enables a more granular classification, predicting failure information progressively from general failure types (e.g., electrical failure, mechanical failure, etc.) down to specific failure descriptors (e.g., leaking, broken, etc.).

2.7 Hyperparameter Tuning

To further refine the selected models and minimize prediction error, hyperparameter tuning is performed. This optimization process relies extensively on cross-validation. Cross-validation serves not only to assess model effectiveness and mitigate overfitting, as highlighted by Brodeur et al. (2020), but also to identify the optimal hyperparameter configurations that yield the lowest test error.

In this study, hyperparameter tuning is conducted independently for each model type. The regression model employs K-Fold cross-validation, suitable for general regression tasks. The classification model utilizes PanelSplit cross-validation, a technique designed for time-series cross-validation involving multiple entities (i.e., multiple wells). The respective cross-validation schemes are illustrated in Figure 5 and Figure 6.

Prior to initiating hyperparameter tuning, learning curves (plots of training and testing scores against varying amounts of training data or training iterations) are analyzed. These plots help

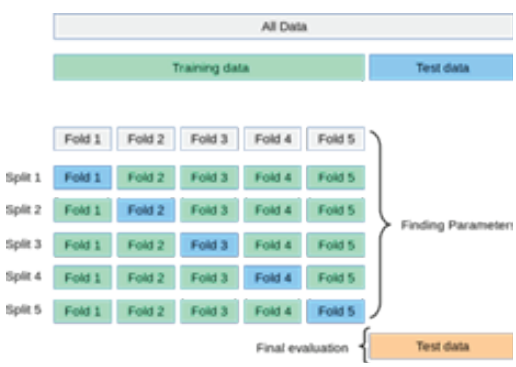


Figure 5. *K-Fold cross-validation.*

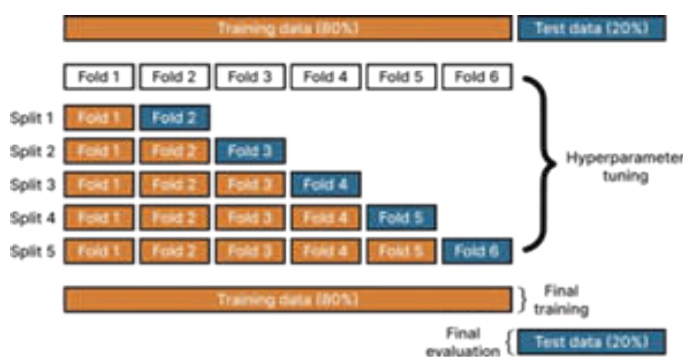


Figure 6. *PanelSplit (time-series split) cross-validation.*

in understanding the model's fitting tendencies, such as bias and variance, thereby guiding the hyperparameter search strategy. A well-fitted model typically exhibits converging training and testing scores with low error, indicating good generalization performance on unseen data.

3. RESULTS & DISCUSSION

3.1 ML/AI Model Evaluation

Following the model development workflow in this study, 4 modules for this study was obtained, which includes virtual rate model, automatic sensor trend analysis, pump health indexing, and failure information prediction.

a. Virtual Rate Model

Four virtual rate regression models have been developed, one for each category of well production rate. The well production rate category can be seen in Table 2. By utilizing feature selection and feature importance function, it was found that the models perform better with these features: “BFPD”, “PBHP”, “PBHT”, “Ampere”, “Pump Stages”, “Motor HP”, “Volt”, and “PSD”. The accumulation of four virtual rate regression models score can be seen in Table 3.

Table 2. *Well production rate category.*

Min Rate	Max Rate	Category
0	1500	Low
1500	3500	Medium Low
3500	10000	Medium High
10000	30000	High

b. Failure Information Prediction

Using the preprocessed features—which include the original sensor data, time-shifted values (previous and next timesteps), and derivative-based metrics—Machine Learning models were developed and undergo a model selection function using the proposed performance metrics in which Light Gradient Boosting Machine (LGBM) algorithm was

Table 3. *Regression models score.*

Model	MAE	MSE	RMSE	R2	RMSLE	MAPE
Extra Trees Regressor	106.69	25561.53	159.82	0.74	0.36	0.29
Random Forest Regressor	110.94	26098.10	161.47	0.73	0.37	0.30
Extra Gradient Boosting	116.24	27301.00	165.18	0.72	0.38	0.31
Light Gradient Boosting Machine	123.98	28958.14	170.12	0.70	0.38	0.34
K Neighbors Regressors	129.20	35363.64	188.01	0.64	0.42	0.35

selected. After extensive hyperparameter tuning, the model was subsequently integrated into a hierarchical classification framework to support multi-level failure classification tasks. The final model's performance metrics are presented in Table 4.

Table 4. *Hierarchical classification model score.*

	Accuracy	Precision	Recall	F1-Score
1st Level	0.93	0.93	0.93	0.93
2nd Level	0.62	0.70	0.62	0.62
3rd Level	0.54	0.71	0.54	0.55
4th Level	0.61	0.77	0.61	0.62
Combined	0.50	0.63	0.50	0.50

The original prediction results in the table are labelled as “combined” in which it can be separated into four hierarchical levels, each of which can be evaluated independently: failure type (Level 1), failure item (Level 2), specific failure item (Level 3), and detailed failure descriptor (Level 4).

3.2 Real World Application

In order to validate the end-to-end workflow, two wells were selected as a case study, N-20 and R-02. These wells were selected based on their substantial data availability on the event of trip and Downhole Problem (DHP).

a. Virtual Rate Model

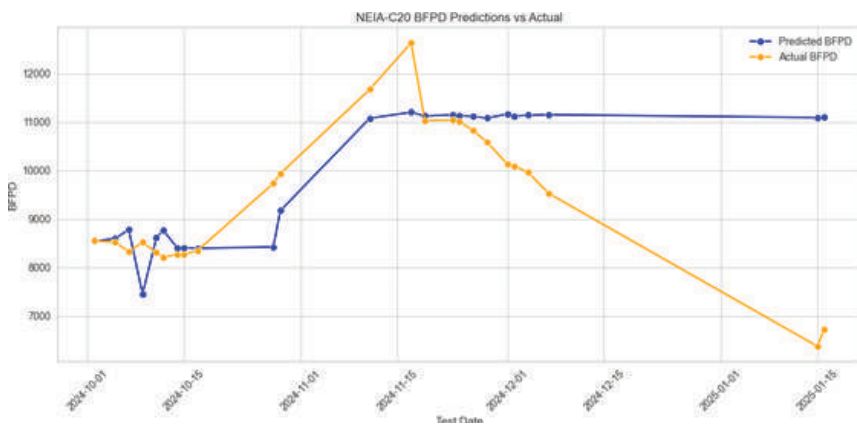


Figure 7. *Virtual rate BFPD vs well test BFPD (N-20).*

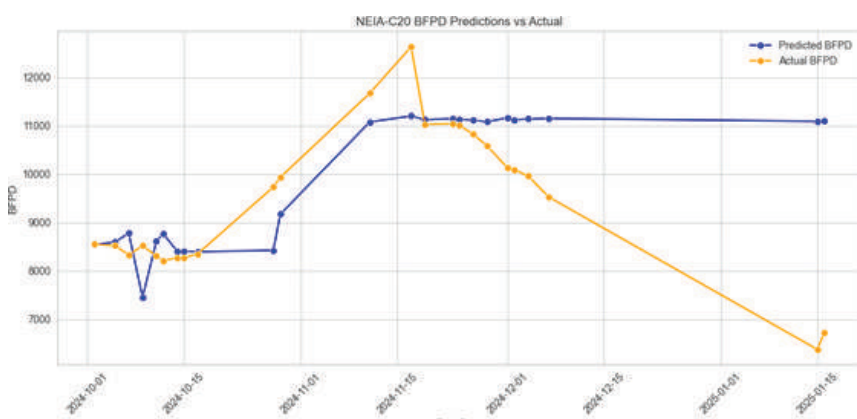


Figure 8. *Virtual rate BFPD vs well test BFPD (R-02).*

Based on historical data, well N-20 was declared to DHP on 21 January 2025, while well R-02 experienced a trip on 7 February 2025. These cases illustrate a key limitation of the virtual rate model: its predictions may become less reliable in the days leading up to a DHP event as shown in Figure 7. This is likely due to the presence of abnormal sensor behavior, which the model identifies as anomalous, since it was trained primarily on data from normal operating conditions. However, during steady-state operation or trips, the model remains robust as shown in Figure 8—successfully tracking the actual production rate trend with reasonable accuracy.

b. Automatic Sensor Trend Analysis

Based on historical records, the N-20 well experienced a trip event on 21 January 2025, categorized under the "High Motor Temperature (TM)" trip mode, which eventually led to DHP declaration. Using the automatic sensor trend

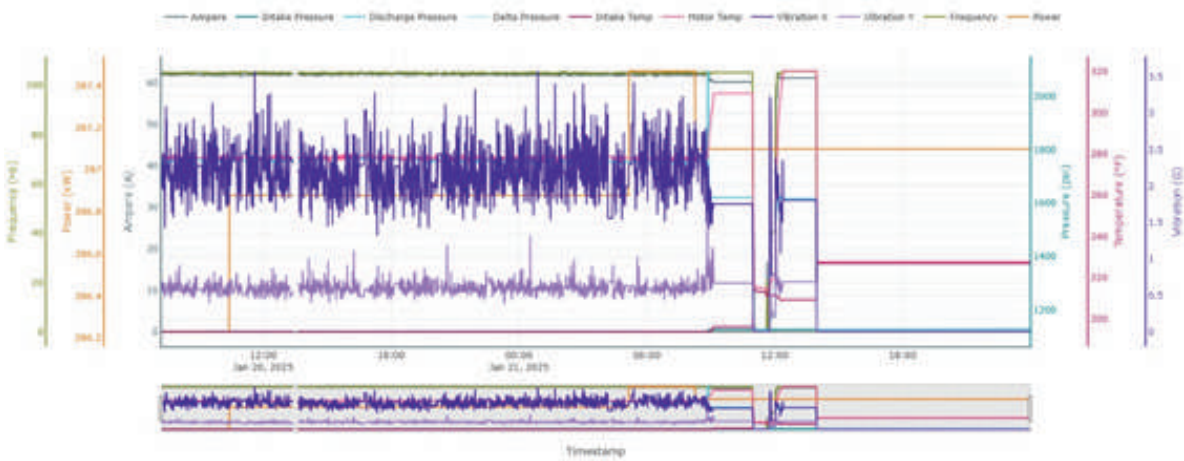


Figure 9. *N-20 well sensor data.*



Figure 10. *R-02 well sensor data.*

analysis on the data range shown in Figure 9, the algorithm identified a likely cause for the "High TM" trip: pump stage plugging. A similar pattern was also observed in the sensor data of the R-02 well shown in Figure 10, where both the historical data and the algorithm's output indicated pump stage plugging as the probable root cause.

c. Pump Health Indexing

Figures 11 and 12 present sensor data from the day of the trip and the preceding day for both wells. When compared against the historical timeline of trip events, the anomalies detected by the PCA–T^2 monitoring model align closely with the actual trip occurrences. This correlation is evident in the rising T^2 values leading up to the event, as shown in both figures. These results demonstrate the model's ability to reliably identify abnormal operating conditions in advance—conditions that typically precede an ESP trip. This reinforces the model's potential as an early warning system for proactive intervention.

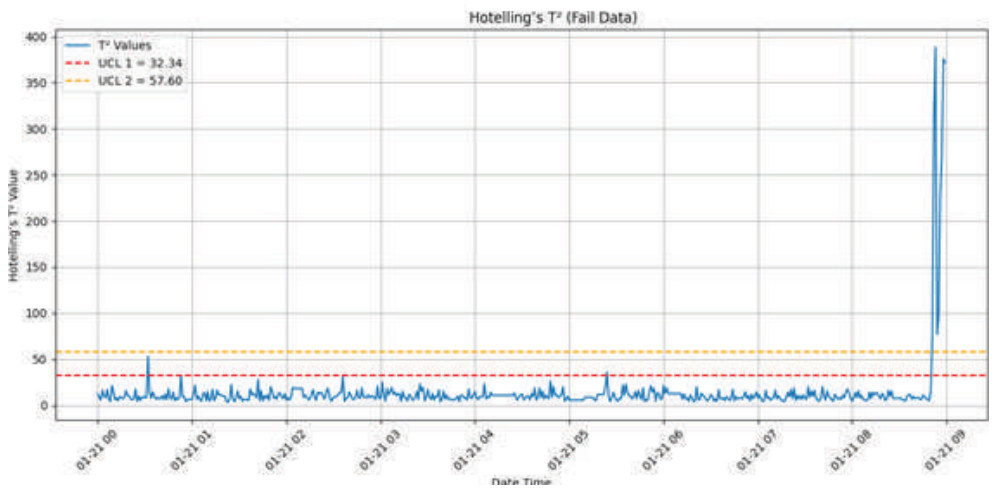


Figure 11. *N-20 Hotelling's T2 graph.*

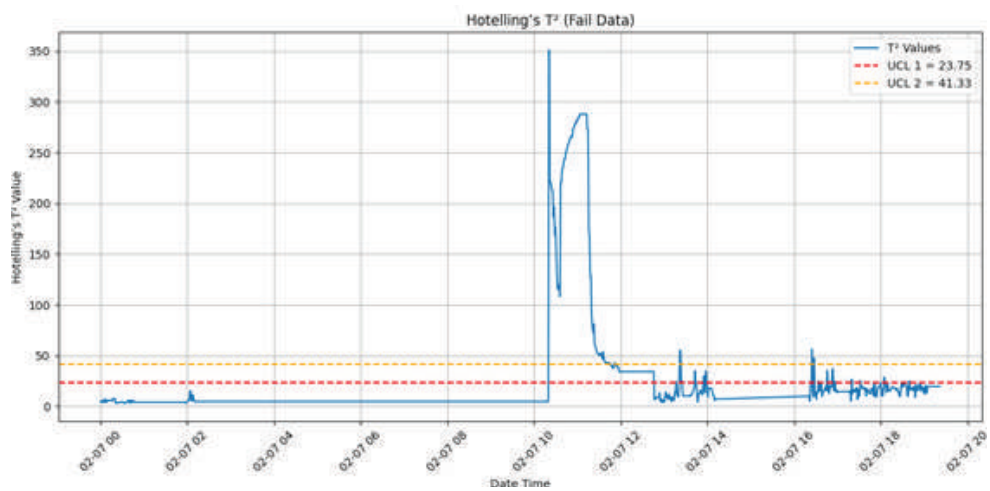


Figure 12. *R-02 Hotelling's T2 graph*

d. Failure Information Prediction

Since the N-20 well was declared DHP, the developed ML model was applied to its preprocessed sensor data to support preliminary Root Cause Analysis (RCA). The goal was to help identify the underlying failure mode and inform optimization strategies for the upcoming ESP replacement. Following the ESP pull, the failure was confirmed to be an Electrical Downhole Problem (EDHP), with the main cable identified as the failed component. The specific issue was a rupture in the cable's insulation.

Using sensor data from the 7-day period leading up to the DHP event, the ML model successfully predicted the failure as EDHP, with the failure item classified as the main cable, and the specific failure as insulation rupture and short circuit. This prediction was made with a confidence level of 99.83%, correctly identifying the failure information down to the third hierarchical level.

In the case of well R-02, since the ESP is still operational, detailed failure information has not been confirmed or logged in the historical database. However, the trip event can still be used as a reference to evaluate the model's behavior. When the model was applied to the preprocessed sensor data from the 7 days preceding the trip, it predicted MDHP (Mechanical Downhole Problem), with the failure item identified as tubing, the specific part as the body, and the failure mode as leaking—at a confidence level of 76.38%.

Although this result differs from the output of the automatic sensor trend analysis—which associated the trip with pump stage plugging—the ML model's prediction is still plausible. A tubing leak could result in reduced fluid levels, impairing motor cooling and potentially triggering a "High TM" trip. It is also important to note that the failure classification model was designed primarily for post-DHP conditions (i.e., when the ESP is offline). The detailed classification results for both wells are provided in Table 5 and Table 6.

Table 5. *Failure information prediction results (N-20).*

Level 1	Level 2	Level 3	Level 4	Confidence Rate
EDHP	Main Cable	Insulation	Short Circuit	99.83%
MDHP	Protector	Bag	Rupture, Burst	0.17%

Table 6. *Failure information prediction results (R-02).*

Level 1	Level 2	Level 3	Level 4	Confidence Rate
MDHP	Tubing	Body	Leaking	76.38%
MDHP	Pump	Shaft	Broken	16.92%
MDHP	Protector	Shaft	Broken	6.70%

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INTELLIGENT ANOMALY DETECTION FOR COMPRESSOR SYSTEMS USING MACHINE LEARNING TO AVOID UNPLANNED PRODUCTION STOP: CASE STUDY IN PT PERTAMINA HULU MAHAKAM

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ABSTRACT

Ensuring turbine compressor systems' availability, reliability and efficiency is critical in gas processing and delivery operations. Unplanned failures can lead to costly downtime and reduced operational performance, causing unsuccessful production targets. This study emphasizes implementing machine learning-based anomaly detection to revolutionize the monitoring and maintenance of turbine compressor performance in PT Pertamina Hulu Mahakam (PHM) fields. The objective is to capture and investigate as well as mitigate anomalies that may indicate instrument and/or equipment failures, sensor anomalies, and performance degradation to enable proactive intervention before major disruptions occur through Big Data System App developed by Technology Development I (TD I) – Technology Innovation (TI) – Dit. SPPU, PT. Pertamina (Persero).

The methodology involves historical data learning, data trend analysis, and anomaly detection modelling. Single-Variable regression analysis is utilized to establish relationships among key operational parameters, while univariate anomaly detection techniques such as Isolation Forest (I-Forest) and One-Class Support Vector Machine (OC-SVM) are applied to detect abnormal patterns. The dataset comprises historical turbine compressor operation data, focusing on critical indicators such as Flow Differential Pressure (Flow DP), Surge Margin, Suction Pressure, Discharge Pressure, and Anti-Surge Valve Position. Model training and testing were conducted on data spanning several months in 2024, with contamination factor adjustments tailored to each subsystem to optimize detection accuracy.

Key findings reveal that OC-SVM demonstrates superior anomaly detection capabilities compared to I-Forest, particularly in identifying anomalies associated with instrumentation failures and unstable turbine compressor operations. A total of 85 anomaly instances were detected in specific test cases, leading to the refinement of anomaly thresholds for improved precision. In addition, a subsystem filtering approach was introduced, allowing for targeted anomaly detection on critical

turbine compressor components. The results were successfully integrated into PHM's PI Vision monitoring system, providing real-time data visualization and facilitating rapid decision-making, indeed connected to the headquarters office via web-based online monitoring. In conclusion, this implementation joint study demonstrates that machine learning-driven anomaly detection is a powerful tool for optimizing gas turbine compressor performance, availability, and reliability at PT Pertamina Hulu Mahakam through advanced predictive maintenance monitoring systems as well as cost optimization programs. Integrating OC-SVM-based anomaly detection into operational workflows enhances fault detection efficiency and predictive maintenance strategies. future research could explore deep learning-based forecasting techniques as a potential avenue for enhancing predictive maintenance.

Keywords: Machine Learning, Big Data, Predictive Maintenance

1. BACKGROUND

The turbine-driven low-pressure compressor system plays a vital role in ensuring the stability and productivity of gas processing and delivery operations, particularly in the upstream oil and gas sector. In high-demand environments such as PT Pertamina Hulu Mahakam (PHM), maintaining the availability, reliability, and efficiency of turbine compressors is crucial to meeting production targets and minimizing costly operational disruptions.

Unplanned shutdowns caused by instrumentation issues, sensor anomalies, or process instability remain a major operational risk. These failures not only lead to lost production but also increase emergency maintenance costs and equipment degradation. To mitigate these risks, the adoption of predictive maintenance strategies powered by Big Data and machine learning has become increasingly essential. Such systems enable early detection of deviations, allowing timely and informed decision-making (Lee et al., 2014).

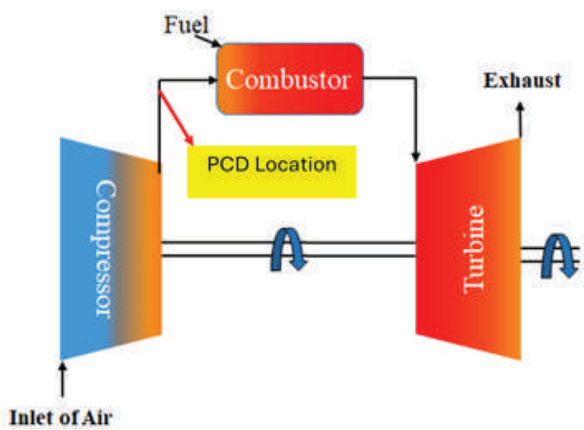


Figure 1. *Schematic diagram of a turbine-driven compressor systemModification Scope*

A key parameter in this context is the Pressure Compressor Discharge (PCD), which reflects the health and operating condition of the compressor. Maintaining PCD within the optimal range ensures smooth transitions in airflow and pressure to the combustor and turbine stages. As illustrated in Figure 1, PCD is located immediately downstream of the compressor and serves as a vital performance indicator for system integrity and efficiency.

To address this operational need, this study investigates the use of machine learning-based anomaly detection, specifically Isolation Forest (I-Forest) and One-Class Support Vector Machine (OC-SVM), applied to historical and real-time turbine compressor data at PHM. The implementation is supported by the Big Data System App developed by Technology Development I (TD I) – Technology Innovation (TI), Directorate of SPPU, PT. Pertamina (Persero), enabling centralized anomaly detection and proactive maintenance.

2. LITERATURE REVIEW

Traditional approaches to monitoring and maintaining compressor systems in the oil and gas industry have typically relied on manual inspections, scheduled maintenance, and threshold-based alarms. While these methods have been effective to an extent, they often lack the sensitivity to detect subtle anomalies or incipient failures that develop under dynamic operating conditions. As a result, these limitations can lead to unplanned downtimes, inefficient resource utilization, and increased operational risk (Mobley, 2002).

The rise of machine learning (ML) in industrial operations has opened new possibilities for predictive maintenance, particularly through anomaly detection techniques that can uncover abnormal patterns in large-scale operational data. Unlike traditional rule-based systems, machine learning models can dynamically adapt to changing system behavior and identify anomalies without predefined thresholds. Among the most widely used unsupervised anomaly detection methods are the Isolation Forest (I-Forest) and One-Class Support Vector Machine (OC-SVM). These algorithms are especially well-suited for cases where fault data is scarce or unlabeled, making them ideal for industrial settings where anomalies are rare but impactful (Liu et al., 2008; Schölkopf et al., 2001).

In parallel, the development of cyber-physical systems (CPS) and industrial big data platforms has enabled the integration of machine learning models into real-time operational workflows. Lee et al. (2014) emphasized the role of CPS in supporting real-time analytics, fault diagnostics, and operational optimization in Industry 4.0 environments. Such platforms allow for continuous monitoring, automatic anomaly notification, and centralized visualization via dashboards—significantly enhancing response times and decision-making processes.

Despite these advances, the application of ML-based anomaly detection in turbine-driven low-pressure compressor systems remains underexplored—especially in real-world upstream field operations like those at PT Pertamina Hulu Mahakam (PHM). Most prior studies emphasize lab-scale testing or general-purpose predictive maintenance solutions rather than fully deployed systems utilizing live operational data in the field. To contextualize the position of the proposed approach, Table 1 presents a comparative overview of three anomaly detection paradigms—threshold-based methods, supervised machine learning, and unsupervised ML techniques such

Table 1. *Comparative Overview of Anomaly Derection Methods*

Criteria	Threshold-based Detection	Supervised ML	Unsupervised ML (OC-SVM, I-Forest)
Data Requirement	Low	High	Medium
Adaptability to Changing Patterns	Low	Medium	High
Real-time Capability	High	Medium	High
Needed for labeled Data	No	Yes	No
Robustness to Noise	Low	Medium	High
Scalability	Medium	High	High
Interpretability	High	Medium	Medium

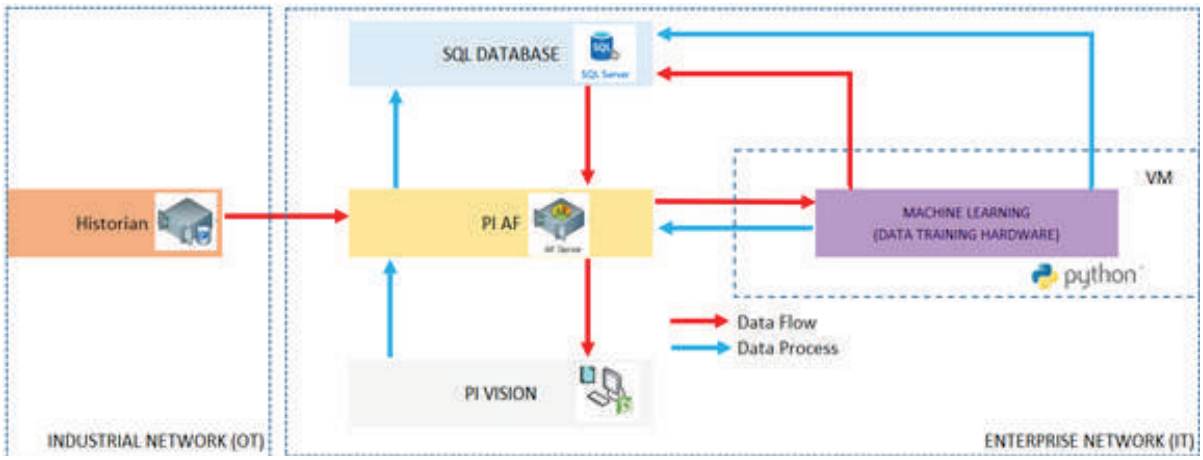


Figure 2. *Data Flow and Processing Architecture for Real-Time Data-Driven System*

as OC-SVM and Isolation Forest—highlighting their respective strengths and trade-offs in terms of data needs, real-time application, and scalability. as OC-SVM and Isolation Forest—highlighting their respective strengths and trade-offs in terms of data needs, real-time application, and scalability.

3. METHODOLOGY

This study applies a layered machine learning methodology to detect anomalies in the performance of turbine-driven compressor systems at PT Pertamina Hulu Mahakam (PHM). The implementation is supported by a real-time Big Data infrastructure developed by Technology Development I (TD I) – Technology Innovation (TI), which facilitates data ingestion, model training, anomaly detection, and visualization in an integrated ecosystem. The system is built on a hybrid OT–IT architecture, where operational data from field sensors is first captured through a Historian system on the Industrial Network (OT). This data is then transferred into the PI Asset Framework (PI AF), which acts as the centralized data layer bridging to both SQL databases and analytical tools. Figure 2 provides the architectural backbone for data processing in this study. Once raw data is aggregated in PI AF, it is periodically exported to a Python-based machine learning environment hosted in a virtual machine (VM) for model development. From this point, the modeling process involves two primary stages: trend modeling using multivariable regression and anomaly detection using univariate outlier models.

In the first stage, a multivariable regression model is built to capture the relationship between Flow Differential Pressure (Flow DP) as the target variable and its correlated operational parameters. This regression aims to generate baseline predictions and identify deviations in trend behavior. The best regression model is selected through AutoML scoring, with evaluation based on R^2 values to ensure high goodness-of-fit.

In the second stage, anomaly detection is performed using two algorithms:

- Isolation Forest (I-Forest), which isolates anomalous data points based on random partitioning trees.
- One-Class Support Vector Machine (OC-SVM), which defines a decision boundary around the normal operating region.

The models are trained using 1-minute interval data across April to May 2024. Each subsystem (e.g., Compressor–Performance) is treated independently with tailored contamination factors ranging from 0.0001 to 0.001, based on

observed data distribution and prior anomaly history. This tuning improves detection precision while minimizing false positives.

4. RESULTS AND DISCUSSION

The performance of the anomaly detection models was evaluated using data collected from April to May 2024, with a focus on the Flow Differential Pressure (Flow DP) and related parameters across compressor subsystems. The modeling results show the effectiveness of multivariable regression in trend capturing, and the comparative performance of Isolation Forest (I-Forest) and One-Class Support Vector Machine (OC-SVM) in detecting abnormal behavior based on univariate deviations. Figure 3 illustrates the multivariable regression results, which show a strong correlation between Flow DP and key features such as Suction Pressure, Discharge Pressure, and Anti-Surge Valve Command. These relationships validate the feasibility of using regression residuals as a foundation for anomaly detection. The model achieved a high R^2 value,

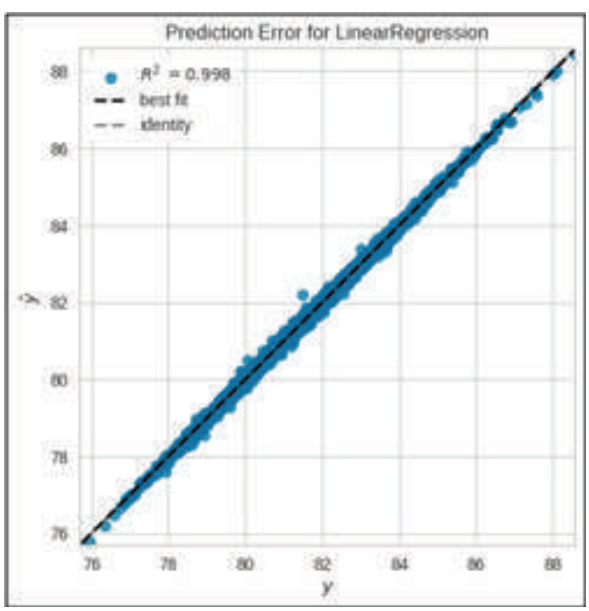
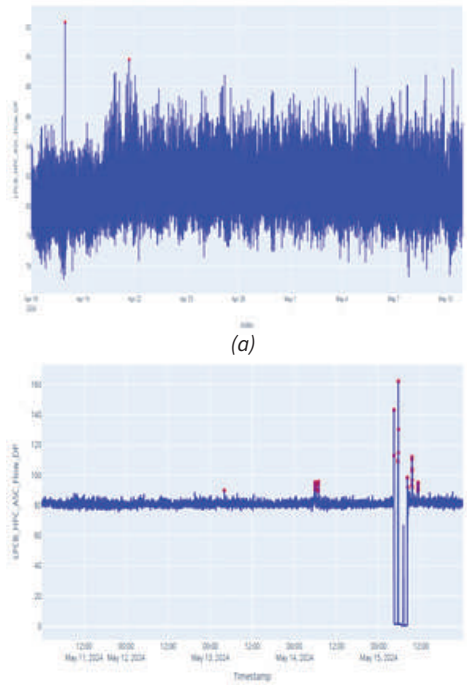


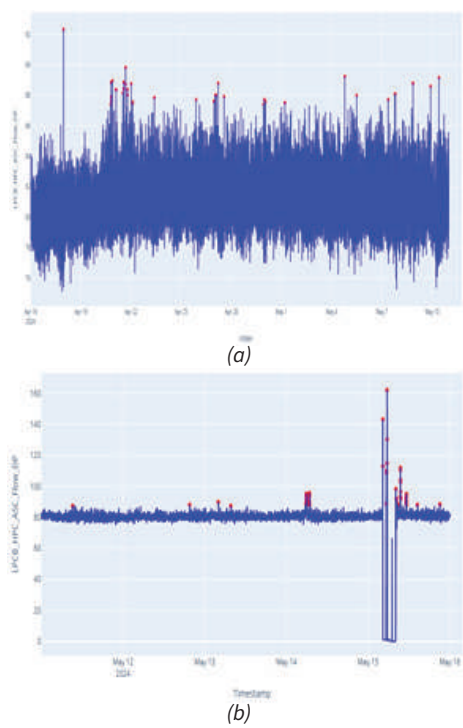
Figure 3. *Multivariable regression results showing correlation between Flow DP and other variables*



(a)

(b)

Figure 4. *Performance using I-Forest with Contamination Factor 0.0001 (a), Training Data Results (b), Testing Data Results*



(a)

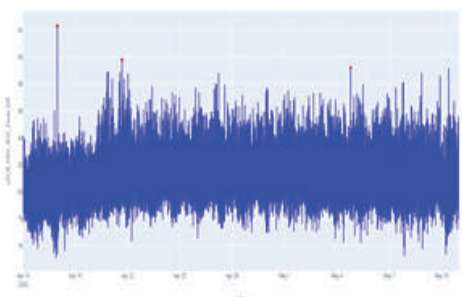
(b)

Figure 5. *Performance using I-Forest with Contamination Factor 0.001 (a), Training Data Results (b), Testing Data Results*

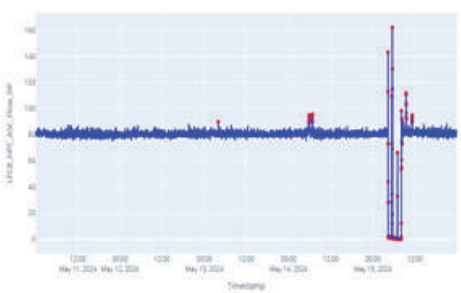
indicating good trend predictability for baseline behavior.

Subsequent modeling using I-Forest with contamination factors of 0.0001 and 0.001 (Figures 4 and 5) reveals that while the algorithm is able to detect major outliers, it tends to be less sensitive to early-stage deviations or subtle instrumentation anomalies. This is reflected in the concentration of anomalies only during peak outlier points, with fewer indications in pre-failure intervals.

In contrast, the OC-SVM model (Figures 6 and 7) demonstrates a significantly higher sensitivity to gradual deviations. Anomalies are more evenly distributed over the pre-shutdown timeline, especially when contamination is set to 0.001. This aligns with the expected behavior of OC-SVM in capturing boundary violations in compressed distributions, making it better suited for early warning detection.

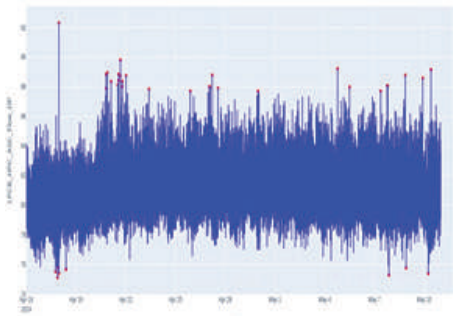


(a)

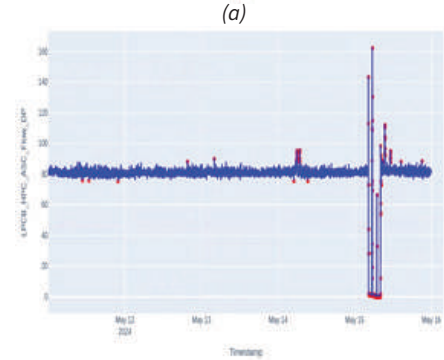


(b)

Figure 6. *Performance using OC-SVM with Contamination Factor 0.0001 (a), Training Data Results (b), Testing Data Results*



(a)



(b)

Figure 7. *Performance using OC-SVM with Contamination Factor 0.001 (a), Training Data Results (b), Testing Data Results*

Based on backtesting around a real system shutdown event in May 2024, the OC-SVM model proved more effective in identifying anomalies that preceded the incident. The anomalies were primarily linked to small but persistent deviations in Flow DP and Anti-Surge Valve command behavior. Consequently, the OC-SVM configuration with contamination factor 0.001 was selected for deployment. After model validation, the detection

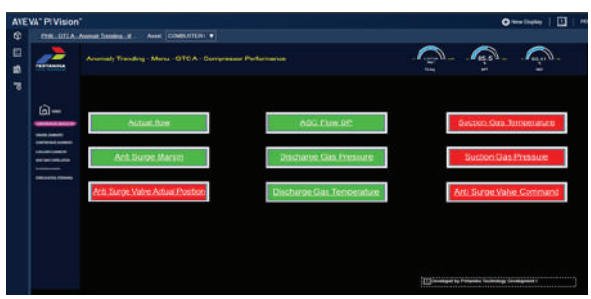


Figure 8. *Anomaly Detection Visualization on PI Vision Display in the Sub-System Compressor – Performance.*



Figure 9. *Visualization on PI Vision Display - ASC Flow DP Anomaly Trending*



Figure 10. *Visualization on PI Vision Display - Anti Surge Valve Command Anomaly Trending*

system was operationalized into PI Vision for real-time field monitoring. Figure 8 shows the anomaly output in PI Vision for the Compressor – Performance subsystem, where red indicators highlight periods with detected abnormalities. Figure 9 visualizes the anomaly trending over time for ASC Flow DP, while Figure 10 displays the same for the Anti-Surge Valve Command.

5. RESULTS AND DISCUSSION

The results of this study demonstrate the potential of combining data-driven modeling and machine learning to improve the early detection of operational anomalies in turbine compressor systems. Key takeaways from the implementation and evaluation are summarized as follows:

1. Machine learning-based anomaly detection, specifically using OC-SVM and I-Forest algorithms, has proven effective in identifying abnormal behavior in real-time compressor operation at PT Pertamina Hulu Mahakam.
2. The use of multivariable regression modeling established a reliable baseline for operational trends, enhancing anomaly scoring accuracy by leveraging key features such as suction pressure and anti-surge valve position.
3. OC-SVM outperformed Isolation Forest in detecting early-stage deviations and subtle instrumentation anomalies, with the best results achieved using a contamination factor of 0.001.

4. The final model was successfully integrated into the PI Vision platform, enabling real-time visualization of anomaly trends and supporting proactive responses to potential equipment failure.
5. This study confirms the applicability of unsupervised learning techniques in predictive maintenance frameworks and opens avenues for future work involving deep learning-based forecasting for long-term anomaly prediction.

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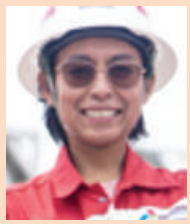


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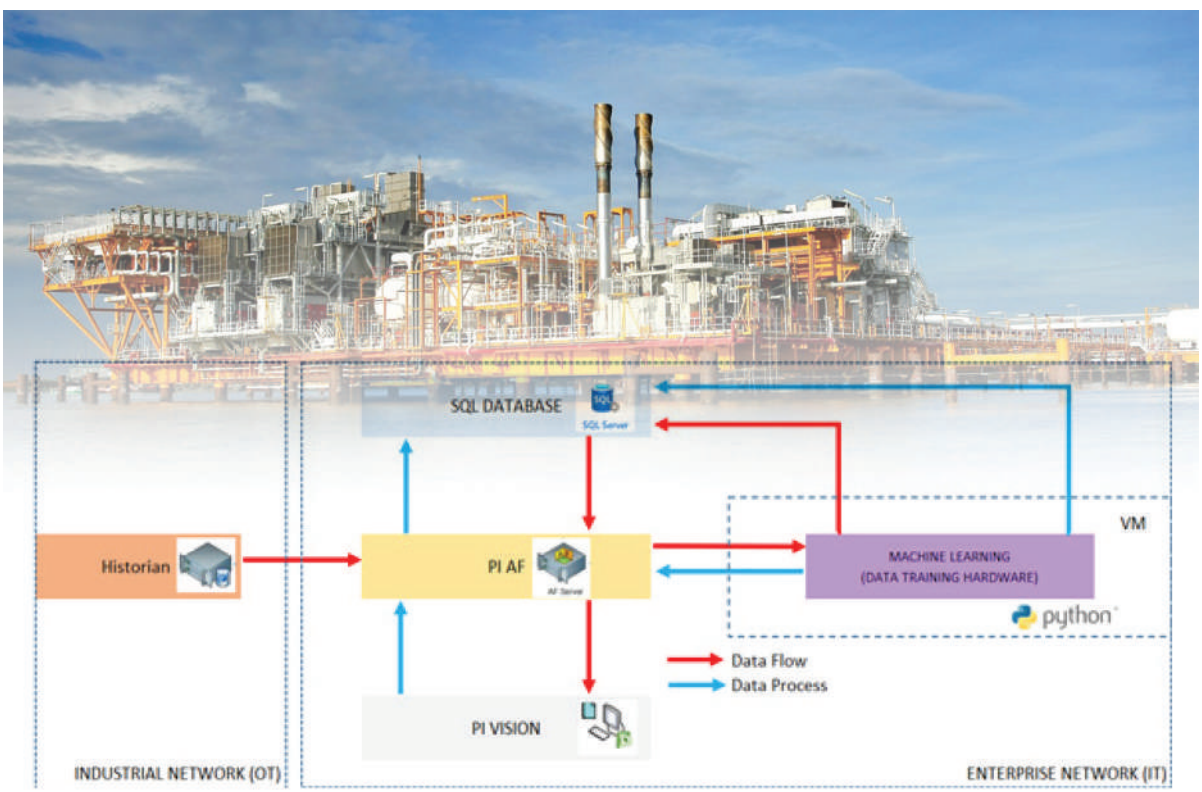


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